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REPORT OF THE COMMITTEE ON A TREATISE ON MARINE ECOLOGY AND PALEOECOLOGY

1948 - 1949

HARRY S. LADD, CHAIRMAN

VICE - CHAIRMEN:

GORDON GUNTER, FOR BIOLOGY
KENNETH E. LOHMAN, FOR GEOLOGY
ROGER REVELLE, FOR OCEANOGRAPHY

Division of Geology and Geography
National Research Council
Washington, D. C.

NATIONAL RESEARCH COUNCIL
2101 Constitution Avenue
Washington 25, D. C.

December 1949

NATIONAL RESEARCH COUNCIL

DIVISION OF GEOLOGY AND GEOGRAPHY

WASHINGTON, D. C.

* REPORT OF THE COMMITTEE ON A TREATISE ON MARINE ECOLOGY AND PALEOECOLOGY

1948 - 1949

Presented in preliminary form as Appendix 5
at the Annual Meeting of the Division
April 23, 1949

* (No. 9 in this Series. See page 121
for list of previous reports.)

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REPORT OF THE COMMITTEE ON

TREATISE ON MARINE ECOLOGY AND PALEOECOLOGY

INTRODUCTION

No formal meetings of the Committee were held during the year but the Chairman and Vice-Chairman Lohman conferred on many occasions with members resident in Washington; several members were visited in the field and others made trips to Washington where they conferred with local members. On April 21, 1949 Ralph W. Imlay, following the completion of his section of the Treatise, delivered an address before the Paleontological Society of Washington on "Paleoecology of the Jurassic Seas of the Western Interior". Dr. Imlay's contribution to the Treatise is included in the present report.

Two new members have been added to the Committee: Dr. Roland Brown of the U. S. Geological Survey and Mr. Joel Hedgpeth of the University of Texas. Dr. Brown will be responsible for editing units of the Treatise as they are submitted and Mr. Hedgpeth will collaborate with Dr. Gunter in the preparation of the ecological part of the Treatise.

TREATISE ON MARINE ECOLOGY AND PALEOECOLOGY

GENERAL

Progress in the preparation of the Treatise has speeded up appreciably during the past year. A number of units of the work have now been completed and the Committee has a much clearer idea of the probable size of the several sections. As a result it has seemed desirable to make some changes in the organization of the Treatise. The ecological part of the Treatise and the Annotated Bibliography of Marine Ecology will be combined to form Volume One, the section on Paleoecology with the Annotated Bibliography of Paleoecology will be combined to form Volume Two. It is estimated that each of these volumes will total approximately 1,000 printed pages, including illustrations.

Part I, dealing with marine ecology, is well underway as Vice-Chairman Gunter spent approximately half of the year at the Scripps Institution of Oceanography and also visited the Woods Hole Oceanographic Institution. Dr. Gunter will be assisted by Mr. Hedgpeth and also by specialists who will prepare the sections dealing with special environments. Dr. A. S. Pearse of Duke University is preparing the section on beaches. One new assignment has been made in connection with the Annotated Bibliography: Prof. Claude E. ZoBell will prepare the section dealing with the Bacteria.

Part II deals with paleoecology. One completed chapter was published in last year's Annual Report but it now appears that this excellent chapter (Paleoecology of the Early Ordovician Sea in Central Texas by Preston E. Cloud, Jr. and Virgil E. Barnes) will have to be somewhat shortened if it and other chapters on paleoecology are to be included with annotated bibliographies in one volume. Two additional chapters (the Cambrian by Christina Lochman and the Jurassic by Ralph W. Imlay) are included in the present report. These are shorter and, it is believed, of suitable length; other chapters may be still shorter, but none should be longer.

CLASSIFICATION OF MARINE ENVIRONMENTS

The need for a uniform and workable classification of marine environments has been felt by the Committee. Although complete agreement may never be achieved by all workers in the broad fields of marine ecology and paleoecology, the variable and often contradictory meanings associated with such terms as littoral, neritic, bathyal, etc., has emphasized the need for a definite classification to be adopted for the Treatise.

With this in mind, the Chairman and Vice-Chairman for Geology held a number of meetings with Professor Siemon W. Muller of Stanford University, who has long been concerned with this problem. As a result of these meetings, Professor Muller prepared a chart which he called a "Compilation of Bathymetric Classifications" showing the classification used by (1) Sverdrup, Johnson, and Fleming, (2) Grabau, (3) Diener, (4) Neaverson, (5) Haug, (6) Twenhofel and Shrock, and (7) Pia. Copies of this chart, together with a three-page summary prepared by Professor Muller and a questionnaire asking which classification was preferred were sent to all members of the Committee and to a number of other interested specialists. The response was prompt and enlightening. The returns from over 20 questionnaires contained several additional classifications and many valuable suggestions. From this material the chart on the next page was prepared.

Obviously, all points of view could not be represented on one chart, and some wide divergences of opinion have not been resolved. For example, it was discovered too late to make a change, that the division between the bathyal and abyssal zones would perhaps be much better at 4000 meters instead of 2000 meters, as shown.

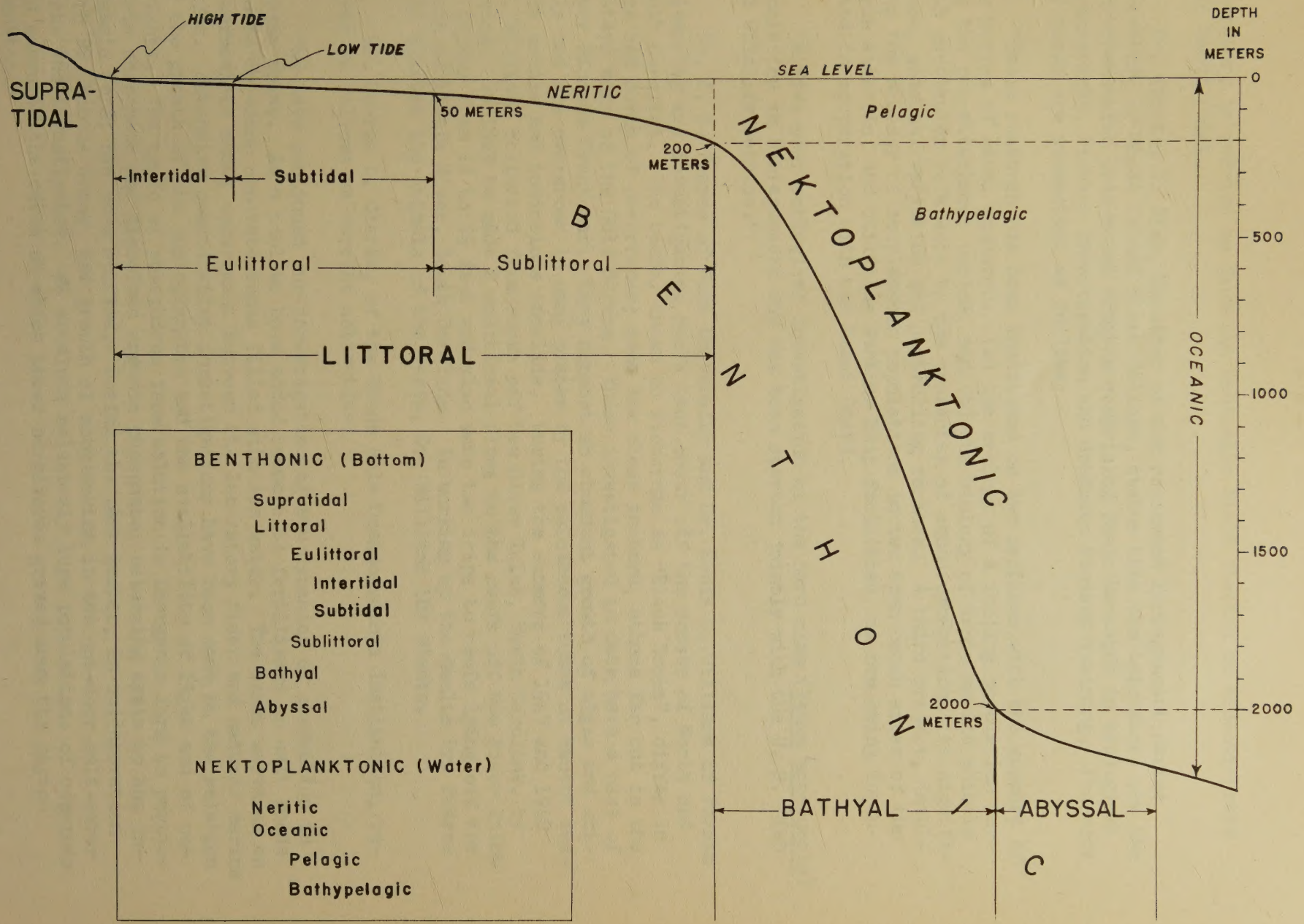
Suggestions regarding changes in this classification will be welcomed by the Committee in order that the one adopted for use in the Treatise will be as accurate and comprehensive as possible. The terminology used in the different chapters of the Treatise will be geared to the classification finally adopted.

CURRENT ACTIVITIES

EASTERN UNITED STATES

Chesapeake Bay Institute. The staff at present consists of Dr. Donald W. Pritchard, Director, Dr. Wayne Burt, Oceanographer, Dr. Dayton C. Carritt, Marine Chemist, Dr. H. H. Whaley, Ecologist, three chemical technicians, and five members of the boat crew. Dr. Carritt, formerly of Scripps Institution of Oceanography and the Woods Hole Oceanographic Institution, is now occupied with developing equipment for the improvement of chemical research work in the Chesapeake Bay area. Dr. Whaley, formerly with the U. S. Fish and Wildlife Service, is conducting field work in physical oceanography. To date, 126 stations have been established in the Chesapeake Bay and have been occupied twice. The third survey of the stations will begin in October of this year. A new boat, 62 feet long with a 16-foot beam, designed especially for estuary work, and having a 16 x 18 foot laboratory, is now under construction and will be ready for work by Christmas, 1949. Field work for the

Classification of Marine Environments



laboratory is carried on from the Annapolis field station on Rideout Creek near Sands Point.

Dr. Charles J. Fish, Director of the re-opened Narragansett Marine Laboratory of Rhode Island State College, states that the Laboratory now has a comprehensive year-round program comprising Basic Research in biological oceanography, Fishery Investigation and Graduate Student Training. Projects and plans are summarized as follows:

"Basic research has been instituted on two problems with the support of the Office of Naval Research: (a) the ecology of a fouling population during the pre-attachment period, and (b) the biology of sonic marine animals with particular reference to the character of sound production, its significance, seasonal variation and controlling factors. A third project, involving the ecology of zooplankton populations in two open ocean areas of the North Atlantic, and utilizing Weather Ship facilities, is now being formulated in cooperation with the Coast Guard.

"A five-year ecological investigation of the hard clam (Venus mercenaria) population in Narragansett Bay has been started jointly with the U. S. Fish and Wildlife Service."

Dr. A. S. Pearse of Duke University and Dr. Louis G. Williams of Furman University are investigating reefs that occur off the coasts of North and South Carolina. The reefs, known to fisherman as "Black Rocks", differ in size and depth of occurrence; some lie close inshore, others far out in the western edge of the Gulf Stream. Those investigated to date have a base of lower Miocene Trent marl; they support an abundant growth of algae and animals and are overgrown in many places by the calcareous tubes of Recent sessile snails and tubicolous annelids. During the summers of 1947 and 1948 Dr. Williams collected from rocks off New River Inlet, North Carolina, by diving. In 1949 he made 8 additional dives to the reefs off New River Inlet at depths from 12 to 55 feet and also made two trips to reefs lying off the mouth of Little River, South Carolina. In working up the results Dr. Pearse will discuss the animals of the reefs, Dr. Williams the plants.

Dr. George L. Clarke, of the Woods Hole Oceanographic Institution, reports as follows on current activities:

"We have continued our investigation of the dynamics of production in marine areas. As a tool we have added commercial fertilizers to salt ponds and to out-door concrete tanks filled with sea water. The tanks serve as an intermediate model experiment between the laboratory flask and natural marine areas. Intensive quantitative investigations have been made on the relation of the growth of the phytoplankton and the availability of light and of nutrients. The cycle of phosphorus from solution in inorganic form to particulate phosphate and dissolved organic phosphate, returning again to the inorganic form, has been studied. During the past summer, in collaboration with Dr. Fabius Gross, the growth of zooplankton in the out-door salt-water tanks was investigated. We obtained relatively huge populations of copepods and measured the rates at which these herbivores grazed down the phytoplankton."

MIDDLE UNITED STATES

The mudlump phenomena of the Lower Mississippi Delta are currently being studied by H. V. Andersen and James P. Morgan of the Louisiana State University Geological Department staff. The investigation is being conducted for the New Orleans District, Corps of Engineers under the Division Engineer Lower Mississippi Valley Division. Mr. Andersen has submitted the following brief report:

"Mudlumps are apparently unique to the Mississippi River. Some are islands, others are concealed beneath the water. Those observed have been formed beyond the mouths of the distributaries of the Mississippi River and are composed of fine-grained mud (clay) which varies in color and in quantity of associated organic remains. This clay, with the exception of a fossiliferous variety present in some of the mudlumps, is tough and resistant to wave action when completely or partly submerged.

"The mission of the present investigation is to solve, if possible, some of the mudlump problems which are of concern to the Corps of Engineers. Of the many questions left unanswered by previous investigators, three of vital interest to the sponsor of this study are: 1) the lateral limits of the mudlumps, 2) the amount of vertical displacement of the material, and 3) the original area of deposition of clay in the present mudlumps.

"Detailed mapping of the mudlump areas augmented by a fathometer survey of the Gulf between and beyond the periphery of the islands has enabled Morgan to delineate the lateral extent of some mudlump groups.

"The major problem, so far, has been to determine the amount of vertical displacement of the material in the mudlumps. The portable coring equipment which could be transported to the mudlumps had a limited penetration potential. In actual operation on the mudlumps, however, it was found that the depth of penetration can not be predicated on the amount of pipe the equipment is capable of forcing into the ground. The controlling factor appears to be the degree of plasticity of the clay. According to Morgan, one hole dug in the center of a mudlump would not remain open long enough to permit taking cores below the 40 foot level. Needless to say, the total thickness of the clay mass has not been determined by mechanical means, but is known to be in excess of 115 feet.

"The animal remains in the mudlump clays were expected to offer little other than evidence as to the original environment of deposition. With the discovery of an extremely fossiliferous, glauconitic clay (containing the remains of such microscopic organisms as ostracodes and foraminifers, and such large organisms as pelecypods, gastropods, bryozoans, and corals) came a possible answer to the vertical displacement problem which had not been

solved by coring. A conclusion which could be drawn, although admittedly inaccurate in many details, is that the present position of the mudlump fauna minus the depth below sea level of the same fauna now living in the Gulf would approximate the amount of vertical movement of the mudlump clay.

"A number of samples from the near-shore environments in the delta and from the mouth of South Pass (the central major distributary of the Mississippi River) seaward to a depth of 400 feet were collected in 1948 and 1949. A cursory examination of these samples shows that they have only a negative value in locating the environment of the mudlump fauna. The foraminiferal remains in the 400-foot sample off the mouth of South Pass have the closest affinity to the mudlump fauna, but a sufficient number of differences prevents considering the two correlatives.

"On the basis of the present series of off-shore samples in the possession of the author, it is apparent that environmental conditions similar to those occupied by the mudlump fauna, when living, will be found beyond the area of active delta growth at the present mouth of the Mississippi River. This assumption can be corroborated by many samples in a series taken off the Texas and Florida coast which the author has examined from the collections of S. W. Lowman (Shell Oil Company) and F. W. Rolshausen (Humble Oil Company).

"The present status and future prospects of the paleontological research in connection with the investigation of mudlumps can be easily summarized. A taxonomic analysis of the foraminifers in the mudlump fauna is being prepared. This will be followed by a detailed analysis of all environments sampled by the author and any additional off-shore samples from the Gulf of Mexico which can be obtained in order to secure the environment of the living correlative of the mudlump fauna."

In 1947 the U. S. Geological Survey with the support of the Office of Naval Research carried on a gravity survey of an area in the Gulf of Mexico lying south and southeast of the mouth of the Sabine River. In addition to the gravity work, bottom samples were collected and oceanographic observations made along three profiles extending at right angles to the shore from points close to the beach for distances of 75 miles to points where the water depth is about 125 feet. Jeffery D. Frautschy of the University of Southern California is studying the physical characteristics of the bottom samples and Orville L. Bandy also of U. S. C. has now undertaken a parallel study of the contained Foraminifera. Mr. Bandy's work is sponsored by the U. S. Geological Survey and supported by the Office of Naval Research. He is analyzing the foraminiferal assemblages in an attempt to correlate them with changes in ecological conditions, all samples being accompanied by data regarding depth, temperature, salinity and other environmental factors.

A field season of three and a half months has been completed by Norman D. Newell and a party of six to eight co-workers investigating the

environmental conditions under which the Permian reeflike limestones of West Texas were formed. This is the first of several seasons' work to be devoted to this project which is sponsored jointly by The American Museum of Natural History and Columbia University, and the Humble Oil and Refining Company.

During the summer of 1949, intensive field investigations were carried on continuously in the Guadalupe Mountains and Delaware Basin with incidental excursions to the Apache Mountains, the Sierra Diablo and the Glass Mountains. Conclusions regarding the paleoecology of the Permian reefs are to be drawn from a large number of field observations on primary structures, from the petrology of the limestones and associated sediments, and from the distributions of fossils. Approximately five tons of specimens were collected and are now being studied in the laboratories of Columbia University and The American Museum of Natural History. Field data are in the process of being assembled in a form of detailed facies maps.

In order to obtain better perspective and background data applying to this research in paleoecology, Dr. Newell and his group plan several weeks in the Andros Island region of the Bahamas late in the spring of 1950.

It may be noted that this research program is coordinated with that of G. A. Cooper and his associates at the U. S. National Museum with respect to the faunas of the Permian of West Texas.

Texas A. and M. College has established a Department of Oceanography under the leadership of Prof. Dale F. Leipper and plans to initiate a study of oceanographic problems peculiar to the Gulf of Mexico.

The laboratories of the Institute of Marine Science of the University of Texas have been opened at Port Aransas, Texas. Dr. Gordon Gunter has been named Acting Director. The efforts of the staff at the present time are being devoted to an extensive investigation of the oyster, the program being directed and supported by the Texas A. and M. Research Foundation. The Institute plans in the future to provide facilities for qualified visiting investigators and advanced students.

Dr. Heinz Lowenstam reports as follows on recent activities in connection with the paleo-temperature investigation being carried on by Dr. H. C. Urey and his research group at the University of Chicago:

> "Recent activities include the development of an improved method of sample preparations which assures reliable reproducable data on the oxygen isotopes in carbonate skeletons and, the establishment of a precise empiric scale. The empiric scale is based on specimens and assemblages of Recent marine organisms secured during the summer from known depths, together with accurate data on temperature ranges and water samples. The specimens for the low and middle temperature range were collected by Dr. R. Buchsbaum, who secured his material, with the aid of the Marine Biological Station, from a number of points along the Pacific Coast from the Friday Harbor's area southwest to Lower

California, Mexico. Those for the higher temperature range were secured by the writer in the Bermuds in shore waters with the aid of the Bermuda Biological Station. Tank experiments under controlled temperature conditions were set up by Dr. Buchsbaum at a number of West Coast stations. The material from Bermuda included shell material of Pinna and Strombus gigas regenerated over a short period of time.

"In the paleo-temperature investigation the question of possible preservation of seasonal effects was investigated by determining the isotopic abundance of successive growth stages in in Jurassic belemnites from Scotland. Variations of a cyclical nature of oxygen (and also of carbon) isotopes, repeated successively though not of identical magnitude were found. These results are most encouraging as they establish beyond any doubt the fact that paleo-temperatures, as recorded by oxygen isotope ratios in certain types of carbonate skeletons such as belemnites are preserved at least as far back as the Jurassic. We do not know as yet, however, whether the cyclical temperature variations recorded in the 'growth rings' of the belemnites represent seasonal fluctuation, seasonal migration records from shallow to deeper waters or seasonal migration from cooler to warmer waters.

In addition to working with Dr. Urey on paleo-temperature, Dr. Lowenstam continued his paleo-ecologic studies of the Niagaran reefs in the Great Lakes areas. He states:

"An analysis was made of the reef builders and reef dwellers as found on the various types of reefs to determine the environmental effects on assemblage above and below wave base. Data were also gathered on the pioneer populations of these reefs. In order to allow a proper perspective of the Niagaran reefs in relation to reefs in general, brief comparative studies were made on Carboniferous and Permian reefs in the Texas-New Mexico region and three months were spent at Bermuda to secure comparative data on the existing reefs there. Attempts to determine the gross composition, of the inshore and outside reefs, by means of estimating species ratios were made. These data were obtained by means of diving and swimming over the reefs with a face mask. Specimens and sediments were collected in the reef lanes and basins by means of diving, and a number of sample and dredging traverses were made extending from half a mile north of North Reef southward through Harrington Sound, to a quarter of a mile south of the southern 'boilers'. Material from the interior of some of the mound or chapeiro-like reefs were obtained by Captain Dale of the Government Dredge Boat in the shipping lanes inside the northern pseudo lagoon."

WESTERN UNITED STATES

K. O. Emery and R. E. Stevenson of the University of Southern California have begun a general survey of the ecologic and oceanographic problems of estuaries and salt marshes, particular attention being paid to those of the California coast.

The Pacific Marine Station at Dillon Beach, California, a branch of the College of the Pacific, is now in its second full year of operation. The plant at present consists of two buildings, laboratory and warehouse, on the shore of Bodega Bay just above the mouth of Tomales Bay. The station operates a diesel-powered boat 37 feet long equipped for light dredging. Activities so far have consisted primarily of teaching, but the area offers opportunities for marine ecological investigations of all types of beaches and bay environments. The station has the beginnings of a library and a reference museum containing several thousand specimens of marine invertebrates.

Dr. Fred B. Phleger has recently transferred his activities from Amherst College, Mass., to the Scripps Institution of Oceanography at La Jolla, California, where he will devote his efforts to ecological problems of the Recent Foraminifera of the West Coast. Dr. Phleger has recently completed a manuscript on the distribution of Foraminifera in the northwestern part of the Gulf of Mexico and one (in collaboration with William R. Walton) entitled "Ecology of Marsh and Bay Foraminifera, Barnstable, Massachusetts."

James Steele Williams and V. E. McKelvey of the U. S. Geological Survey report as follows on current ecologic studies of the Phosphoria fauna:

> "Ecologic studies of the Phosphoria (Permian) fauna are progressing according to plan. During the 1949 field season collections of fossils were made from some 25 new trenches or exposed sections in Idaho, Wyoming, and Montana by Jack Smedley and Walter Record, Jr. Additional but mostly smaller collections were made from Permian rocks by some 18 to 20 other members of the Federal Geological Survey who were working in Rocky Mountain States. Nearly all the collections were obtained from relatively thin lithologic zones in measured sections. Many of the recently made collections were cataloged and locality and stratigraphic data concerning them were plotted on assembly sheets during the winter. Fossils from many of these collections were prepared and are being segregated for study by specialists. Paleontologic studies of the invertebrates, begun some years ago, are being continued with the new material. Recently discovered fossil fish remains are being studied by D. H. Dunkle.
>
> "Field data recorded for each collection include the following: lithology of the unit from which collected; percentage of the rock composed of fossils; recognizable phyla and classes and approximate percentage of each; recognizable genera and species and approximate percentage of each type; mineral composition, and conditions of preservation; evidence of reworking; sizes of fossils or fragments; distribution within bed or zone and relation to different lithologic types of the zone; orientation of specimens; special modes of occurrence; and other miscellaneous data. The results of extensive sedimentation studies, for which field data comparable to the above are being collected by McKelvey and associates, will later be available for coordination with the records of the fossils.

"The paleontologic and related studies are being made by James Steele Williams and associates. Stratigraphic, sedimentational, economic, and other investigations are under the direction of V. E. McKelvey. Some units of the stratigraphic studies have been issued. It is planned to publish units of the paleontologic studies separately as completed, but to later bind them together in several large volumes into which will also be incorporated broad scale interpretations of the faunal relationships and paleogeography."

OUTSIDE THE CONTINENTAL UNITED STATES

An Arctic Research Laboratory has been set up at Point Barrow, Alaska, under the technical supervision of Johns Hopkins University with the support of the Office of Naval Research. The program is a continuing one that has now beencarried on for a period of about two years. Dr. G. E. MacGinitie, the Director, reported August 31, 1949, that most of the group have been busy with research on marine invertebrates whenever time and weather permitted. He states:

"The new boat is proving to be very satisfactory for the work planned. It is used not only for dredging and for collecting ecological data to fill out the report on the distribution and abundance of marine invertebrates of the region, but for the oceanographers as well.

"The weather has been almost consistently bad since the Ship Expedition. This may be due to the fact that the temperature of the ocean water has been running between five degrees and nine degrees C. On September 1, we recorded a temperature of five degrees at a depth of 130 feet. The prevailing winds have been quite strong from the East and make it hard to get much done, even on those days that we can go out. One dredge haul was made at 741 feet, which was at the bottom of a canyon, 12 miles offshore. The ocean floor on the polar side of this canyon was 504 feet deep and the inner side was 438 feet. The bottom of the canyon, which is about a quarter of a mile across, is muddy and covered with a mass of worm tubes. Although at these greater depths we collected a number of animals that have not been previously taken, on the whole it was found that fauna does not vary greatly with depths beyond 100 feet. Since the temperature is uniform, this is to be expected, for temperature is a much more important distribution factor than pressure."

Work on a final report on the submarine geology and reefs of Bikini Atoll in the Marshall Islands has been continued by K. O. Emery, J. I. Tracey, Jr., and H. S. Ladd of the U. S. Geological Survey, and Gordon Lill of the Office of Naval Research, and associates, with some sections of the main report and several of the special reports on organic groups completed. The ecological study of the smaller Foraminifera started by Dr. J. A. Cushman has been continued since his death by Misses M. Ruth Todd and Rita Johnson. The core obtained by the British from the deep hole drilled on Funafuti has been borrowed from the British Museum and the officials of the Tohoku University at Sendai, Japan, have loaned the core obtained from the deep hole drilled on Kita-Daito-Zima (North Borodino Island).

At the National Museum Dr. Fenner A. Chace, Jr. is studying the shrimps of Bikini and F. M. Bayer has completed a report on the Gorgonians of the northern Marshalls. Dr. J. P. E. Morrison and associates are preparing a report on the ecology of the Recent mollusks.

Prof. P. M. Hurley of the Massachusetts Institute of Technology is studying coral samples from the upper half of the deep hole drilled on Bikini to test the possibility that either the isotopes of thorium or radium were deposited preferentially out of equilibrium with the uranium in the ocean water during the growth of the corals. Professor Hurley states: "If this is the case, it may be possible to determine rates of coral growth and possibly times of variation of the ocean surface, depending on whether ion- or radium were the dominant less soluble element."

The U. S. Geological Survey, in cooperation with the Corps of Engineers, U. S. Army, is continuing its program of geologic mapping in the Pacific Islands under the leadership of S. K. Neuschel.

In addition to the studies of Bikini, Saipan, and Okinawa mentioned elsewhere, work continued on geologic reports resulting from field work on Yap and in the Palau Islands. A preliminary geologic map of Babelthuap, Palau Islands was completed and photo copied for use of members of the Pacific program, Geological Survey. A geologic map of Angaur, Palau Islands, scale 1/10,000 was completed and is being printed by the Army in Tokyo.

The program of translation of papers concerning the geology and coral reefs of Japan, the Ryukyu Islands, the Marianas, Carolines, and Marshalls, continued. Numerous such translations have been transmitted in typescript to the U. S. Geological Survey and can be examined in the Geological Survey library.

Twelve papers on oceanography and marine biology written by Japanese scientists were translated and reviewed, and will be published in the Transactions of the Pacific Science Congress.

Fossils collected during the process of preparing a geologic map and report of Okinawa are being studied by F. Stearns MacNeil and associates. Mr. MacNeil states:

> "All of the faunas found are characteristic of the Kurosio (Black Tide), the warm Japanese Current. These faunas range in age from upper Miocene to late Pleistocene and compare favorably with late Tertiary and Quaternary faunas described from parts of Japan that were affected by the same current. Even closer relationship probably exists with the late Tertiary faunas of the Philippines, but less complete stratigraphic information is available for the faunas of that area. The deep water faunas of Okinawa, which are tentatively assigned to the upper Miocene and lower Pliocene, show a surprisingly close relationship to the Recent deep water fauna of the Philippines, and practically every species has a nearly identical or closely related analog. The upper Miocene faunas, which occur in both massive and interbedded sands, clays, and marls, and the fauna of the non-calcareous silt and

sand facies of the lowest Pliocene beds appear to have little in common with the known Tertiary and Recent Faunas of the oceanic islands. Probably both the dissimilarity of sedimentary facies, and the apparent restriction of the deeper water elements of the Philippine fauna to the confines of the Japanese Current along eastern Asia are responsible for the difference. The shallow water insular limestone and reef deposits of Pliocene and Pleistocene age contain faunas that are more related to those of the oceanic islands, but the actual species in common are few. Probably the greatest similarity is found in the genus Cypraea of which about a dozen species are found in Okinawa that range throughout the reef-bearing islands of the Pacific.

"The oldest post-Permian rocks on Okinawa are the Shimajiri beds, a thick succession of clays, fine sands, and muds believed to be of upper Miocene age. The Shimajiri beds are found only in the southern part of the island and appear to be faulted against the Paleozoic formations. The uppermost zone of the Shimajiri contains a considerable amount of pyroclastic material. With the exception of the pyroclastics, which probably were derived from volcanoes along the inner arc of the Ryukyus, and the possible derivation of some of the fine sand from fine grained Paleozoic sandstones, the Shimajiri appears not to have been derived from the Ryukyus, but rather represents the fines of deposition from continental Asia. The volume of the Shimajiri, which is in excess of 4,000 feet thick, would seem to make it unlikely that it was derived from the Ryukyu Islands. Mollusca from the Shimajiri indicate deposition in moderately deep water. Comparison of the Shimajiri fauna with the Philippine mollusks recovered by the Albatross Expedition indicates that the species compare most closely with those living at depths of between 100 and 400 fathoms, averaging about 200 fathoms.

"Overlying the Shimajiri beds, and the Paleozoic formations below an altitude of 100 meters, is a sequence of gravels, Ryukyu limestone and reef deposits. Three distinct limestone units are recognized in the Ryukyu, separated from each other by unconformities. The oldest of these is of Pliocene age, the two younger of Pleistocene age. The post-Ryukyu deposits, probably of very late Pleistocene age, are raised beach deposits and dunes, generally highly fossiliferous, which in some cases are located well back from the present beach.

"The oldest Ryukyu limestone unit consists in the lower part of gravels intertongueing with fine sands down the dip, in the middle part of gravels that intertongue with limestone, and in the upper part of limestone that advanced shoreward across the gravelly facies and built up to form a fringing reef. The clastics were of local origin, the sands probably derived largely from erosion of the Shimajiri beds, and the gravels from the Paleozoic formations. The limestone contains few corals but consists largely of Foraminifera, shells of mollusks, Bryozoa, and a large amount of lime debris. The upper part contains a large amount of unattached algal nodules, which suggest deposition in gently agitated, debris strewn areas, presumably lagoons. The Mollusca indicate considerable range in depth conditions. The gravels,

limestones and near shore silts contain forms that normally are collected on beaches and reefs, indicating a shallow water and reef habitat. The basal sandy beds in the most down dip exposures, however, contain forms that inhabit depths of 50 to 100 fathoms.

"The middle limestone unit of the Ryukyu contains less gravel than the oldest limestone, and only one gravel train has definitely been traced into it. In contrast it contains many corals and large parts of it were apparently coral reef. Mollusca collected are all shallow water and reef dwellers.

"The youngest limestone unit of the Ryukyu is usually found as a veneer of debris covering or plastered on older limestones. In one case it is plastered on the underside of a nip cut in the oldest limestone. A few small embayments were filled in completely by limestone. Large coral heads stand upright in it in places. Only one mollusk, an oyster, was found in it."

According to Delos Flint and Raymond Saplis:

"The Okinawa Field Party did reconnaissance geologic mapping of Ishigaki, Iriomote, Miyako, and several of the smaller islands in the southern Ryukyus in the fall of 1948. On Ishigaki Pellatispira-bearing limestone, thought to be Eocene in age, appears to have been deposited in local basins interbedded with sandstone and conglomerate. These beds are overlain by a younger limestone which is largely coralliferous and rubbly but which contains some foraminiferal calcarenite beds in the lower part. The foraminiferal beds and the coralliferous beds are thought to be equivalent to the two lower units of the Ryukyu limestone of Okinawa. Thick deposits of clayey gravels and sands fill the partially enclosed basins between the hill masses on Ishigaki and seem to grade horizontally into the lower calcarenites. These deposits are thought to have been formed by the dumping of terrestrial detritus in sheltered bays and river mouths while calcarenites were being deposited along the outer shores of the island. Work on Iromote revealed rubbly coralliferous limestones which have been deposited along the northern and eastern flanks of the island probably as a fringing reef. The Sonai conglomerate has the stratigraphic relationships of the basal Ryukyu gravels of Okinawa. The Ryukyu limestone of Miyako may be divided into a lower, non-coralliferous, detrital limestone and an upper, coralliferous, rubbly limestone which are similar to the two lower units of the Ryukyu of Okinawa. It is believed that the upper coralliferous limestone represents a reef which developed over an older lagoonal or bank-type detrital limestone, but the exact nature of the contact between the two is unknown.

"Reconnaissance mapping was also done on the islands west of Okinawa, that is on the inner side of the Ryukyu curve. On Kumeshima, beds previously mapped as Shimajiri are now known to be Ryukyu in age. These beds are calcareous, clayey to silty sand marked by typical lower Ryukyu Mollusca. A thick sequence of andesites overlies the limestone on Kume. It is interesting to note that no rocks of Shimajiri age were

found, and that with the possible exception of the tuff beds at Goga on Okinawa, no Shimajiri beds are known on the inside of the Ryukyu arc."

During the past year field work has been carried on in the Marianas Islands by a party headed by Preston E. Cloud, Jr.:

"Saipan has been mapped geologically, field work is presently under way on Tinian, reconnaissance studies have been made on Guam and in the northern Marianas, and marine ecologic studies have been undertaken where personnel, time, and facilities were available."

"As a member of the Army-sponsored party for the study of the geology and soils of Saipan I spent the period from July 1948 to July 1949 in the Pacific and was able to visit and observe in varying degrees of detail certain local features of the marine ecology of the Palau Islands, Guam, Johnston Island, Oahu, Tutuila (American Samoa), New Caledonia, and New Zealand, as well as Saipan itself. With the approval of Army sponsors and the cordial cooperation and effective logistic support of the Navy, detailed reconnaissance studies were made of the marine environments immediately adjacent to Saipan. Pending assimilation and publication of the results of these studies, a statement of the type of work done may be of interest.

"Saipan is located approximately at latitude 15 degrees north and longitude 146 degrees east. Although it is only a pinpoint of 48 square miles in the Pacific, it is, nevertheless, of considerable importance in that it has the greatest variety of reef and shallow-marine environments and the most completely known geologic succession in the Marianas Islands.

"Data obtained in the offshore areas of Saipan include (1) direct observations along lines of traverse of the lagoon-bottom and immediately seaward from the reef, (2) bottom-profiles obtained with a graphically recording fathometer along traverses extending from the reef or shore seaward, and (3) incidental direct observations at many localities not along specific lines of traverse. The positions of the principal traverse-lines are shown in figure 1. Not shown in figure 1 are the positions of supplementary traverses made between the lines of primary direct observation and parallel to the shore, the numerous sites of incidental observation, and the lines of supplementary fathometer traverses.

"Along five principal traverses of direct observation (the more northerly five of figure 1) continuous direct observation was made by means of towing or swimming with a face-mask, by skin-diving, and by diving with shallow-water equipment to depths up to 45 feet. About 90 bottom samples were collected at intervals varying from a few feet to 700 or 800 feet, according to local changes. Collections of the bottom fauna were made at many localities, and dredging was undertaken at a few places.

"Boats and boat crews were provided by the Navy, and bottom sampling and dredging equipment was made in the Navy shops on Saipan. Boats used at different times included a crash boat, a picket boat, rearming and personnel boats, and an air-sea rescue boat in the bottom of which glass ports were installed to permit continuous observation of the bottom. The most useful all-purpose boat was the rearming boat. Diving equipment consisted of an ordinary shallow-water face-mask, a belt of lead weights, and an air line leading to a compressor aboard a rearming boat. Where the water was too deep for easy skin-diving, the bottom fauna was ordinarily collected by diving with the shallow-water gear and loading the desired materials into perforated canvas bags. The bags were then hauled to the surface where their contents were broken up and soft-bodied organisms roughly sorted and bottled on the spot. Dredging proved to be relatively ineffectual with the equipment available and was abandoned after a few attempts. Samples of the bottom sediments were either spot-samples taken by a diver or short-drag samples made with a specially designed small metal bucket. The diving was done by myself and by Chief Boatswain F. X. Jozwick, an enthusiastic and indispensable collaborator throughout the project. For the most part, notes were dictated from the water, or aboard the boat after a diving sortie, to a secretary whose services were provided by the Army's Marianas-Bonins Command.

"The two more southerly principal traverses of direct observation shown in figure 1 were made by swimming, and numerous lines of supplementary traverse were run between the principal traverses and parallel to the shore-line with the glass-bottomed air-sea rescue boat or by towing behind a rearming or personnel boat with a face-mask. Southward from Puntan Muchot to Puntan Agingan (see fig. 1) the front of the barrier reef and the bottom adjacent to it were observed continuously through a face-mask from the end of a line towed behind a rearming boat. At a few other places on the south and northwest sides of the island the reef-front was observed by swimming over the reef at times of light surf. The fringing reefs on the east side of the island and the moats associated with them were observed from shore, but on none of our visits to them was the surf light enough to risk swimming at the reef-front, and restrictions on the use of boats without radios did not permit working the fronts of these reefs in small boats.

"The material collected includes primarily marine benthonic animals, but a good many of the small coral-frequenting fish were collected, as well as a few specimens of larger marine fish, elements of a fresh water fauna in one of the two perennial streams on Saipan, and specimens of some of the commoner marine plants. Both living and dead coral and coralline masses were broken up with hammers to obtain the numerous small animals that live in borings and crannies of various sorts. All of this Recent material has been presented to the Smithsonian Institution for study by its specialists, and identifications furnished by them will comprise important basic data for a contemplated report on the marine ecology of the area.

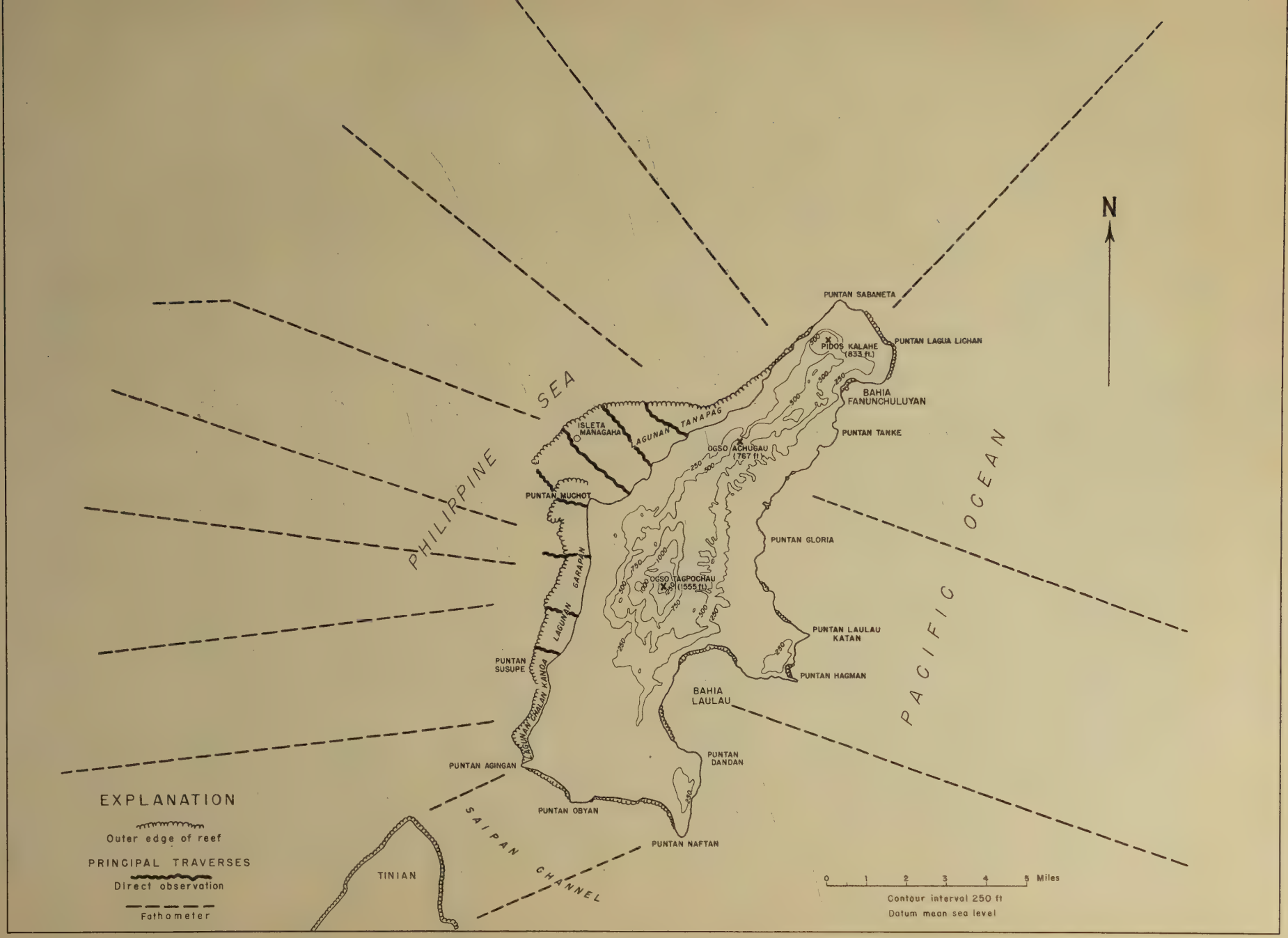


Figure 1. SAIPAN ISLAND, MARIANA ISLANDS
Showing lines of offshore traverses

"The more important discoveries in the marine fauna of Saipan include comatulid crinoids, previously unreported from this area, and the limpet urchin Colobocentrotus mertensi Brandt (identified by A. H. Clark), heretofore known only from the Bonin Islands and a single locality on Guam. The discovery of Colobocentrotus was made by Mrs. Alice Davis, wife of the Army's commanding officer on Saipan, in the surf zone of one of the patches of fringing reef on the east coast. Probably this echinoid would be more widely recorded were its habitat less dangerous for collectors.

"The comatulids of Saipan occur in a zone of actively moving water just inshore from the western barrier reef and not exceeding about 10 feet depth. For the most part they were within 1 to 4 feet of the water's surface. They were found only in an area about 500 yards long and 100 yards wide, although the general ecologic facies in which they occur extends for several miles along the outer margin of the lagoon. Most of them seem to live in fairly open crannies, but a few were seen clinging with their basal cirri to rough surfaces of coral. None were found in a free-floating condition.

"A special study was attempted of the sedimentary significance of holothurians, in an effort to approximate some sort of trituration constant that would serve as a basis for estimating their effect in the breaking up of lagoonal sediments, but it appears that the data from this study have been lost at least temporarily.

"Collecting panels for shipworms were put down at two localities and monthly cumulative and control boards from these are being shipped to William Clench, of Harvard's Museum of Comparative Zoology, for study.

"With direct observations as a basis for interpretation, aerial photographs of the lagoonal waters of Saipan have been studied and an ecologic map of the immediately offshore waters has been prepared, the several types of bottom being classified in accordance with the terminology of Hesse, Allee, and Schmidt[1/].

"Navy aircraft took special oblique aerial photographs of the entire coast-line of Saipan, and these provide invaluable information on the arrangement and concentration of surge channels, as well as other data about the coast, the reefs, and the lagoon.

"It was planned to record pH readings over 24-hour periods for various stations in the lagoon, moats, and tide pools, but after one 24-hour stand on the shore of the lagoon this program had to be abandoned for lack of time and indicator-kits of sufficient delicacy.

1/ Hesse, Richard; Allee, W. C.; and Schmidt, Karl P., Ecological Animal Geography, John Wiley & Sons, Inc., London, 1937.

"As a culminating phase of the program, a series of fathometer traverses was made from the reef outward at various points around the island. These were accomplished by means of a graphically recording fathometer with a range of 2000 fathoms, aboard the Navy's Patrol Escort Craft 899, captained by Lt. J. F. Butler and made available through the courtesy of Rear Admiral C. A. Pownall, then Commander Naval Forces Marianas. These traverses were carried from as near to the reef or shore as the captain of the vessel felt it safe to operate, to a distance in most instances of about 10 miles offshore. The fathometer was kept in constant operation, and, in addition to twelve major traverses along previously selected lines, supplementary traverses were run between end points of all major traverses, parallel to and just offshore from the reef at the northwest side of Saipan, and along a line extending southwestward from the center of the island and oblique to the major traverses shown on figure 1. Data from these traverses have been examined in a preliminary way but only partially plotted. The inspection made and plotting done, however, is enough to indicate that it will be possible to contour the ocean bottom within a radius of 10 miles of Saipan and probably to recognize some persistent submarine scarps.

"Final coordination and interpretation of the studies outlined above, and the much more comprehensive studies of the geology and soils of Saipan, should make this island one of the best known in the Pacific."

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The rudistids, from the biological viewpoint, are good material for an analysis of the phenomena of extinction. They lived from the Rauracian to the Danian. Their appearance, heralded by the genus Diceras, is determined in time and in space; their distribution is relatively well

known, because they are among the fossils sought for and recorded; their last representatives which peopled the Danian of Catalonia, Hippurites (Orbignya) castroi, Agria moroi, Praeradiolites boucheroni, and Praeradiolites leymerii, have been carefully recorded.

The diversity in the organization of the rudistids is marked: The oldest are close to the common bivalves, but the Cretaceous groups, the caprinids, hippuritids, and radiolitids, are so far removed that the naturalists hesitated for a long time before placing them in the taxonomic scale. The right valve is elongated into a cone or rolled into a spiral; the left valve is a simple operculum; the teeth and myophores are vertical plates buried in vertical sockets; and other structures peculiar to different groups are developed. The family continued to increase into the Maestrichtian, which marked the peak of their development. From that time to the close of the Cretaceous, the number of new types and of individuals is diminished.

Bournonia and Durania, because of their vitality, are among the most interesting genera to study. Both genera are widely distributed in the warm seas in northern Africa, southern Europe, and even so far as Cuba, Mexico, and Texas.

Durania, during the Cenomanian, extended its range into southern France and England and to Westphalia; in the Turonian to all of France, Portugal, Egypt, the Apennines, and Texas; in the Senonian to Yugoslavia, Madagascar, Timor, Curaçao, and Cuba.

Internal factors: The shell fixes a large amount of calcite. It grows considerably in height and in thickness, but the cavity remains small, and the ratio between the volume of the shell and that occupied by the animal is a highly specialized character. However, most of the forms, algae, Foraminifera, brachiopods, and mollusks, of Maestrichtian seas, have thick shells.

External factors: A fauna that is developed normally is in harmony with the environment in which it lives and is in equilibrium. If the external factors change, several elements in the fauna may disappear or the percentages of the constituents of the ensemble may be altered. It is to such changes in environment that the authors attribute the disappearance of many groups. In the case of the rudistids, granted that they lived only in waters of a certain depth, at a certain temperature, and only in pure water, any deepening, cooling, or pollution of the water may involve their extinction. Bournonia bournoni, for example, lived with other rudistids in Catalonia and in Aquitaine during the Maestrichtian and became extinct at the end of that period. However, the associated genera developed without interruption and persisted into the marine Danian, indicating that different organisms react in different ways to a changing environment. With Durania, it is a little different, because that genus has shown in the course of its history an unusual tolerance. It is not boxed in the Mediterranean area like most of the rudistids. Nevertheless, it did not survive the upper Maestrichtian, the epoch fatal to most of the rudistids.

The equilibrium upset caused by the disappearance of the rudistids must have been very great. No group has taken their place. The rudistids were fixed, for the most part, and, with the corals, constituted the reefs in the Cretaceous seas. After their disappearance the corals continued to develop alone. A predacious enemy of the rudistid larvae or a parasite may be imagined, but there is no evidence of such a solution to the problem.

Extinction of the last survivors: The last rudistids are recorded in Catalonia. In Catalonia, especially east of Nogueras, the reduced rudistid faunas in the marine formations intercalated in the Danian have somewhat brackish-water characters. Three of these species are peculiar to the Danian, and only Praeradiolites boucheroni is known in the Maestrichtian. In discussing the source of the fauna, the possibility of a sea entering from the east is considered and rejected. The rudistids seem rather to be Maestrichtian types that have evolved in situ, and while a great number of the forms around them have become extinct, they have apparently remained independent of their environment. Change in environment alone cannot be responsible for the death of all the rudistids. The group is like a tree and continues for a long time to put forth new genera, species, and individuals, until finally it loses its creative power. The longevity of a group seems to be in inverse ratio to the rapidity of its evolution (Julia Gardner).

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PALEOECOLOGY OF THE CAMBRIAN IN MONTANA AND WYOMING

by

Christina Lochman[2/]

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2/ Walker Museum, Chicago, Illinois.

INTRODUCTION

A consideration of the paleoecology of the Cambrian sediments of Montana and Wyoming necessitates a tentative statement because of the very incomplete information. Plate I shows the location of all the published and unpublished Cambrian sections in this area that have been measured in sufficient detail to furnish any knowledge pertinent to this study. Scattered collections of fossils have been obtained from not more than two-thirds of these sections, but most of this material is still unstudied. Consequently the interpretations derived from the faunas must be tentative and generalized.

I wish to acknowledge especially the kindness of Charles Deiss, L. L. Sloss, H. D. Thomas and J. V. Barnes who made available unpublished information and sections. In a paper of this kind, much information must be compiled from numerous sources, all of which are acknowledged and cited in the bibliography.

PALEOGEOGRAPHY OF THE AREA

During Middle and Upper Cambrian time, central and eastern Montana and all of Wyoming formed a stable shelf bordering on a miogeosyncline trending through western Montana, southern Idaho and southeastern Utah. This miogeosynclinal area adjoining the relatively stable central shield of North America experienced continuous slow subsidence during Middle and Upper Cambrian time, but the amount was only moderate compared to that of the major axis of the Cordilleran geosyncline which apparently lay still farther west[3], trending through British Columbia, western Idaho, western Utah and Nevada. Thus most of the area under consideration was simply the drowned western coastal plain of Laurentia and Siouxia, a shelf which during the Cambrian received sediments of a dominantly clastic nature and of no great thickness. [4] This surface sloped very gently westward and appears to have had many ridges of Pre-Cambrian quartzite from the Dakotas to Wisconsin. The recent study by Walters (1946) of buried Pre-Cambrian hills in central Kansas indicates that the shelf surface around Siouxia was also irregular. The shelf area experienced its initial downwarping through the early half of the Middle Cambrian, the movement dying out during the deposition of the Elrathiella zone. A second major downwarping began soon after the beginning of the Upper Cambrian and lasted through Dresbachian time. During all of Cambrian time sedimentation was slow, often negligible over large areas, and both coastal and off-shore portions of the shelf were frequently either exposed or just barely awash by the sea.

3/ L. L. Sloss, personal communication, January, 1949.

4/ The average section in Montana of 1,200 ft. represents deposition from early Middle Cambrian into Lower Ordovician, and a maximum thickness of 500 ft. in the northern Black Hills represents the same time, approximately 92 million years.

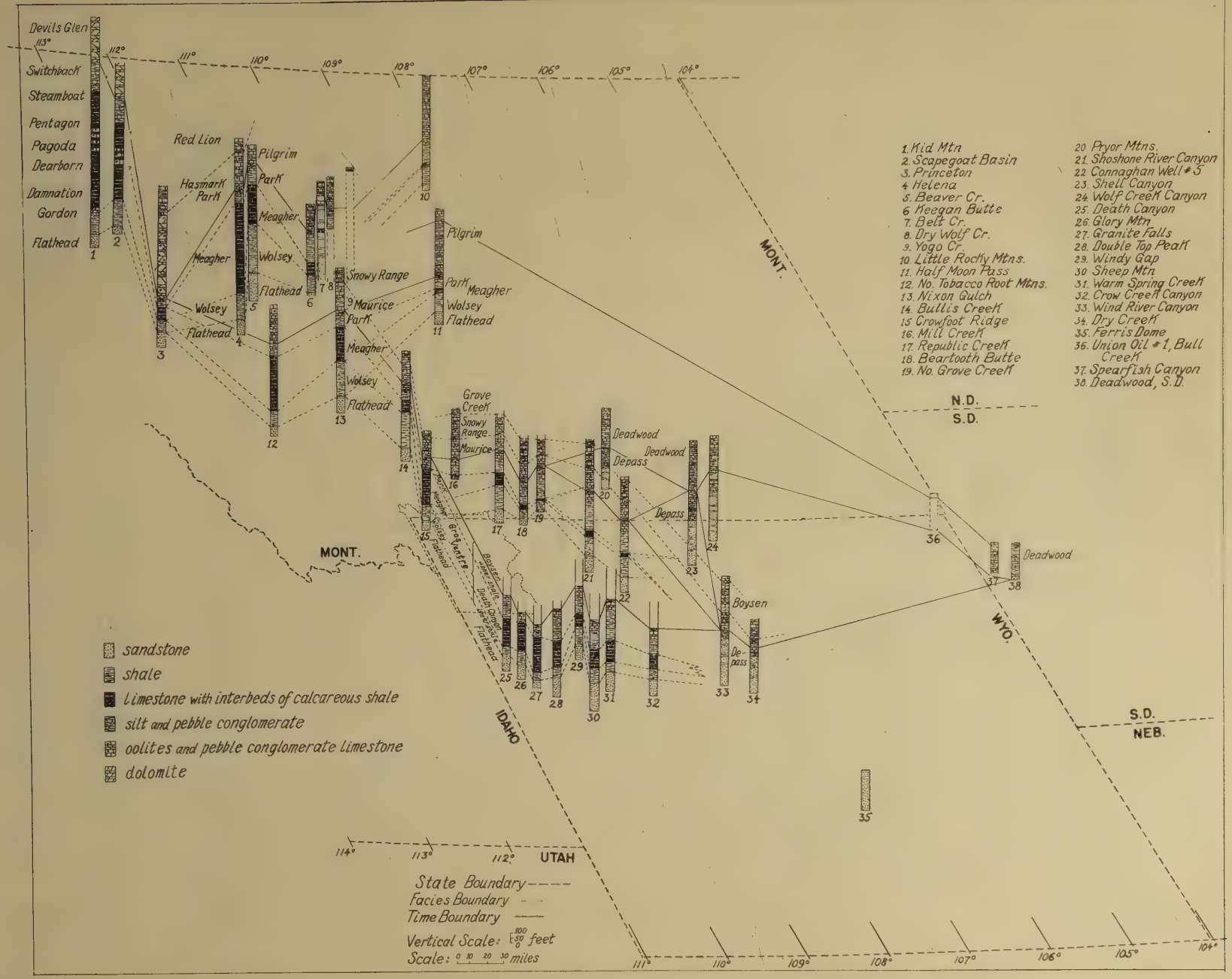

PLATE I-CORRELATION OF FORMATIONS AND FACIES

THE FOSSILS AND THEIR ECOLOGIC IMPLICATIONS

Considering the area and time covered in this study the faunal lists are extremely scanty in both numbers and variety and show clearly our very incomplete knowledge of the Cambrian faunas. Such forms as have been described will be cited by formation, and then a general discussion of the significant features of the faunas will be given.

FORMATIONS OF MIDDLE CAMBRIAN AGE

Flathead formation: No fossils have been reported from the Flathead formation in Montana and only Lingulepis acuminatus has been identified by Miller (1936b) from the top 25 feet of the formation in Wyoming. As L. acuminatus (Conrad) is considered of Upper Cambrian age these Middle Cambrian specimens had best be regarded as an undetermined species of Lingulepis. The probable shore environment of a transgressing sea and the medium to coarse-grained sands of the Flathead mitigated against the preservation of a fauna both at the time of deposition and subsequently. In spite of the absence of fossils, the environment of deposition seems to have been marine.

Gordon shale and Wolsey shale: The fossils of these two formations are considered together since, with one possible exception, they represent the same faunal unit, that of the Glossopleura-Kootenia zone.[5] The exception is an assemblage of species reported by Walcott (1917, p. 18) from the Kid Mountain section of northwestern Montana and emended generically by Resser (1935, 1936) without any comment upon their occurrence. Deiss was unable to duplicate the fauna when he studied the section, although he found members of the Glossopleura-Kootenia fauna in higher beds. Five trilobites of the Albertella zone were reported by Walcott. The fossils of the Glossopleura-Kootenia zone fauna include innumerable worm trails and borings; supposed trilobite trails; 21 species of trilobites; 11 species of brachiopods.

Damnation limestone: This formation is the western lime equivalent of the upper part of the Wolsey, and was deposited in the slowing sinking geosyncline. It carries a fauna which represents the upper half of the Glossopleura-Kootenia zone: worm trails and burrows; 15 species of trilobites; and 3 species of brachiopods.

Lower shale member of the Gros Ventre formation: Stratigraphically and lithologically this member appears to be the equivalent of the Wolsey shale. From it have been reported only worm trails and borings, and the brachiopod, Lingulepis acuminatus (Conrad).

The significant features of the Glossopleura-Kootenia fauna are: an indication from the many tracks and trails of large numbers of soft-bodied animals forming an important constituent of the total fauna, and definite indication of a facies preference among the early Middle Cambrian trilobites, Zacanthoides, Anoria and Glyphaspis, which seem to be partial to silt facies,

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5/ For a recent discussion of the early Middle Cambrian zones and their faunas see Lochman, 1948.

and Glossopleura, Kootenia and Solenopleurella to the lime facies. In contrast no significant preferences appear among the few brachiopods so far described.

Pagoda limestone: This formation, the Pentagon shale, the Meagher limestone and the Death Canyon member of the Gros Ventre formation all contain faunas that belong to the Elrathiella zone. The faunas of this zone are at present known almost exclusively from the studies of Deiss (1939) and Bell (1941). The Pagoda fauna consists of worm trails and burrows; 23 species of trilobites; and 8 species of brachiopods.

Pentagon shale and limestone: The original designation of this formation is somewhat of a misnomer because, lithologically, it contains a good percentage of interbedded limestone, in fact as much as is found in many of the Meagher limestone sections. The described fauna contains 46 species of trilobites; and 7 species of brachiopods.

Meagher limestone: The known fauna contains worm trails and burrows; calcareous algae cf. Tetonophycus sp.; 2 gastropoda--Helcionella sp. and Hyolithes gregarius (M. & H.)--; 15 species of trilobites; and 14 species of brachiopods.

Death Canyon member of the Gros Ventre formation: worm borings; calcareous algae--Aulophycus repens Fenton & Fenton; 6 genera and 4 described species of trilobites.

The faunas of the Elrathiella zone continue to indicate from the many tracks and trails that soft-bodied animals were an important constituent of the total fauna. In addition, the small Helcionella gives the first direct evidence of the gastropoda, and Hyolithes of a possibly allied molluscan group. Direct evidence of calcareous algae also appears. Among the trilobites Bathyuriscus is the only genus still showing a facies preference to shales. Ehmania and Elrathiella appear to be especially cosmopolitan in occurrence. The brachiopods, though more numerous, still show no noticeable preferences.

Steamboat limestone: The relationship of this fauna to those of the preceding formations or to that of the succeeding Switchback shale is not now clear. Very possibly its affinities will be found among the undescribed faunas of the Park shale. The fauna contains calcareous algae; 13 species of trilobites; but no brachiopods are recorded.

Switchback shale: The fauna contains numerous large worm trails; a number of undescribed inarticulate brachiopods; and a few fragmentary undescribed trilobites.

Park shale: The formation appears to contain a large and well developed trilobite and brachiopod fauna but the majority of the species have not yet been described. Most of the described forms occur in the upper 50-75 feet of the formation which is especially fossiliferous. The fauna contains 6 generically determined trilobites; and 2 brachiopods.

The upper shale member of the Gros Ventre formation: The fauna of this shale appears to be equivalent to that of the Park, but like it, is at present poorly known and largely undescribed. The fauna contains annelid trails and burrows; Rivularites; calcareous algae Tetonophycus blackwelderii Fenton & Fenton; 6 species of trilobites; and 5 species of brachiopods.

Depass formation, exclusive of upper 60 feet in type locality: The fauna contains innumerable worm trails and burrows, as Scolithus tubes; 5 species of trilobites; 3 of brachiopods; and 1 species of mollusk--Hyolithes gregarius (Meek & Hayden).

FORMATIONS OF UPPER CAMBRIAN AGE

Devils Glen dolomite: This is the highest formation recognized in northwestern Montana. No fossils have ever been obtained from it, and to date its position in the Upper Cambrian is based entirely upon its stratigraphic position.

Hasmark formation: On the basis of stratigraphic position this formation is clearly the Dresbachian equivalent in southwestern Montana. The only fossil yet observed is the calcareous alga--Aulophycus cf. A. prolificus Fenton & Fenton--which occurs through the upper third of the formation in great numbers.

Pilgrim formation, Dresbach equivalent: Since the Pilgrim formation contains strata equivalent to all of the Upper Cambrian and the Lower Ordovician, the faunas are cited as units to avoid confusion. The lower part of the Pilgrim probably originally contained all three Dresbachian faunal zones, the Cedaria, Crepicephalus and Aphelaspis. However, in the Big Belt Mountains and west side of little Belt Mountains the upper two zones have been removed by post-Cambrian erosion, and in the more eastern outcrops the Aphelaspis zone has not been located in the shaly sections. The Cedaria fauna contains worm trails and borings; small calcareous algae; crinoid and/or cystoid plates; numerous fragments of merostome tests; Mollusca cf. gastropods--Hyolithes sp. undet., Semicirculatea arcuata Lochman; 63 species and subspecies of trilobites; and 4 species of brachiopods.

The Crepicephalus fauna contains worm trails and borings; small calcareous algae; numerous fragments of merostome tests; Mollusca cf. gastropods--Semicirculatea semilunensis Lochman; 35 species and sub-species of trilobites including 4 referred to Crepicephalus; and 4 species of brachiopods.

Maurice formation: From the Horseshoe Hills, Montana, through all of south central Montana and immediately adjoining portions of Wyoming, the strata containing the Dresbachian faunas are, with the exception, locally, of a basal shale and pebble conglomerate, crystalline oolitic and pebble conglomerate limestones that form a prominent cliff on the outcrop, and can be distinguished as a separate formation. Most of the fossils from this region are undescribed. The Cedaria fauna contains worm trails and borings; small calcareous algae; Mollusca cf. gastropod--Semicirculatea arcuata Lochman; one certain gastropod--Hypseloconus parvicostatus Lochman; cf. crinoid and/or cystoid plates; 22 species and sub-species of trilobites; and 5 species of brachiopods.

The Crepicephalus fauna contains 2 species of calcareous algae--Collenia spissa Fenton & Fenton, Aulophycus prolificus Fenton & Fenton; 9 determined and several undetermined species of trilobites including several undetermined species of Crepicephalus; and 3 species of brachiopods.

The Aphelaspis fauna contains calcareous algae--Aulophycus callosus Fenton & Fenton; gastropod--Hypseloconus simplex Lochman; and 4 species of trilobites including Aphelaspis.

Boysen formation: Throughout western and central Wyoming all Upper Cambrian strata are grouped in one formation. In the far western part of the state the entire formation is crystalline limestone, but in the central part, the DuNoir member can be differentiated near the base. The strata which are Dresbachian in age comprise about 75 feet of shale and pebble conglomerate under the DuNoir and the DuNoir member. Evidence of all three faunal zones has been obtained, but the faunas are as yet largely undescribed. The Cedaria fauna contains worm trails and borings; calcareous algae; 8 species of trilobites; and 3 species of brachiopods.

The Crepicephalus fauna contains calcareous algae--Collenia spissa Fenton & Fenton, Aulophycus prolificus Fenton & Fenton; Mollusca cf. gastropod --Hyolithes sp. undet.; 6 species of trilobites in addition to Crepicephalus; and 2 species of brachiopods.

The Aphelaspis fauna contains fragmentary graptolites; and 2 trilobites --Aphelaspis sp., and Pseudolisania sp.

Deadwood formation: In the Bighorn and Pryor Mountains the strata of Upper Cambrian age comprise an indivisible formation most closely related lithologically to the Deadwood formation of the Black Hills, but with a higher lime content. Very little work, even of a reconnaissance nature, has been done in this region. The Cedaria fauna is known to be present as Homagnostus lochmanae Howell & Duncan, Armonia lata (Howell and Duncan), Cedarina prima Lochman have been collected. Tricrepicephalus tripunctatus (Whitfield) indicates the presence of the Crepicephalus fauna; and Aphelapis sp. has been collected from the east side of the Bighorns.

Red Lion formation: This formation overlies the Hasmark in southwestern Montana. Its faunas are not well known, but it appears to be the equivalent of all the Franconian and possibly some Trempealeauian. Only a few specimens collected during field mapping have been described, including 6 trilobites; and 2 brachiopods.

Pilgrim formation: Strata in the middle and upper portions of the formation in all outcrops east of the middle of the Little Belt Mountains carry faunas which indicate their equivalence to the Franconian and the Trempealeauian. Most of these faunas are still undescribed but the following genera may be listed: sponges--Protospongia; worm trails and borings; 14 species of trilobites; and 1 brachiopod.

Snowy Range formation, [6] Franconia equivalent: Intercalated pebble conglomerates and shales overlying the Maurice formation comprise this formation. It is known to carry all the faunal zones of the Franconian but few of the species have been described: numerous worm trails, burrows and borings; calcareous algae--Collenia magna Fenton & Fenton, cf. Aulophycus sp.; cf. crinoid and/or cystoid plates; cf. Mollusca--Hyolithes gallatinensis Resser; 19 species of trilobites; and 17 species and sub-species of brachiopods.

Grove Creek formation, Trempealeau equivalent: In a restricted area in south-central Montana, buff-orange pebble conglomerates, sandy dolomites and shales carrying Trempealeauian faunas have been preserved from erosion. The faunas are still undescribed but several forms may be recorded: worm borings and trails; great abundance of crinoid stems and plates; gastropod-Scaevogyra sp.; 5 trilobites, only generically determined; several undescribed brachiopods; numerous graptolites; merostome fragments.

Boysen formation: This formation contains faunas of Franconian and Trempealeauian age, all largely undescribed. In the Tetons, the Gros Ventre and the west side of the Wind River Ranges, no strata younger than the Conaspis zone are present. On the east side of the Wind River Range the Ptychaspis-Prosaukia zone is present and in the Wind River Canyon of the Owl Creek Mountains beds of Trempealeau age are at the top of the section. The following forms have been recorded: worm borings and trails; Scyphozoa-Laotira cambrica Walcott; numerous graptolites; calcareous algae--Collenia magna Fenton & Fenton; cf. Aulophycus sp.; 13 species of trilobites; and 10 species of brachiopods.

Deadwood formation: The middle and upper strata of this formation in the Bighorn and Pryor Mountains probably contain faunas of Franconian and Trempealeauian age but few fossils have been collected in this region. The known species are worm trails and borings; sponges--Multivasculatus ovatus Howell & Van Houten; and one trilobite--Taenicephalus wyomingensis Resser.

THE ECOLOGICAL IMPLICATIONS

The faunal lists, though incomplete, typify Cambrian faunas in the preponderance of trilobites and inarticulate brachiopods. Probably 75 percent of the Cambrian biotas were soft-bodied plants and animals of whose presence we have evidence now only in the great number and variety of tracks, trails, and borings which are preserved in the fine shales. Yet it is significant that under exceptional conditions of preservation some of these soft-bodied animals have been found, such as jellyfishes, numerous graptolites and several sponges. It can be safely assumed that representatives of all known invertebrate phyla and possibly some unknown primitive phyla were present in the Cambrian seas. Probably primitive vertebrate types were also present. The apparent dominance of the trilobites in the collections of fossils is obviously due to two factors: 1) their having the only preservable test, in the faunas of that time, with the exception of the brachiopods, a few gastropods, and the Echinoderma; and 2) their molting habit which makes available for preservation many carapaces from a single individual.

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[6] Fossils from the formation were labelled "Dry Creek shale" in the old collections of the U. S. National Museum, and were so assigned by Bell (1941) and Resser from 1937 through 1942.

In the numerous collections of fossils listed, several relationships to the lithologic composition of the beds were noted. In the shales of all the Middle Cambrian formations there are local, very fossiliferous zones, where vertical and horizontal positions appear to depend entirely upon fortuitous burial of organic debris. The same holds true for the coquina limestone nodules and patches of fossiliferous matrix in the pebble conglomerates and shales of the Upper Cambrian. In the limestones the fossils may be scattered sparsely through the beds, or locally form a coquina concentration, or again several feet of beds may be quite barren both vertically and laterally. The sections and formations have not been studied in enough detail to evaluate the significance of this distribution. Certainly the majority of the fossil assemblages represent a thanatocoenose, debris piles of shells from dead animals in large part, disarticulated trilobite molts and comminuted brachiopod valves. This is particularly true of the Upper Cambrian beds, from which only one complete trilobite carapace has been obtained. In the Middle Cambrian shales, whole trilobite carapaces are more common; but the absence of free cheeks from most of these specimens, and the presence of disarticulated specimens in the same beds indicate that many of the specimens are probably molts, which have been held together by their burial in the soft silt. Some few collections, such as that in the shales of the Meagher limestone at Nixon Gulch, may contain trilobites which were actually killed by the deposition of the mud. When most of the collections are thanatocoenoses, it is difficult and hazardous to draw definite conclusions as to the habitat associations of the various genera.

Probably only the assemblages of the algal meadows and the Eoorthis and Billingsella "reefs" can be surely regarded as biocoenoses. Though widespread horizontally they are sharply restricted vertically, and have not, to date, furnished very large or significant faunal assemblages.

The varied tracks and trails reported in these formations probably include faecal pellets, and all serve to indicate a large number of soft-bodied animals both moving over and through the lime ooze or fine silt of the bottom, and ingesting it. Such forms would have been representatives of the various worm phyla as well as primitive Crustacea, Arachnida and Mollusca. Local abundance of Scolithus gives additional definite evidence of the activity of marine worms over extensive tidal flats.

The Porifera are represented by two rather small species in the late Upper Cambrian. In both instances they appear to have preferred shallow but clear water sites, probably with a firm bottom.

The Coelenterata are represented in the Upper Cambrian by two planktonic forms, the Scyphozoan, Laotira cambrica, and numerous graptolites. These forms are especially important in giving a picture of the life conditions in the open waters above the shelf area. A normal marine plankton seems to be represented. The jellyfish was clearly stranded on a tidal flat and fortuitously preserved by the silty nature of the sediment. The graptolites have only been superficially examined but no definite sessile forms have been found. They appear to have been fairly abundant over the area, but are preserved only in fine gray shales or in siltstones.

The Echinodermata are represented throughout the Upper Cambrian by plates and stems referable both to cystoids and crinoids. Most of the specimens are isolated plates deposited in the piles of debris in the shale and pebble conglomerate. The animals probably did not live on the bottom where the fossils are now found, but their persistence through the sediments indicates that there were local areas with a firm bottom and shallow, clear water favorable for their development. I believe these areas lay on the shallow platform along the western edge of the shelf because in late Upper Cambrian beds in several sections in south-central Montana, there occur large numbers of crinoid stems, only partially disarticulated, and a small number of isolated calyx plates. This deposit is interpreted as the site of a crinoid colony, inhabited for a considerable length of time, and at no time bothered by any rapid influx of silt.

The Brachiopoda are represented by both inarticulate and articulate species. The inarticulate species of the Middle Cambrian show an interesting cosmopolitan occurrence over the whole shelf area coupled with a noticeable change from formation to formation. Unfortunately this change involves both time and facies, and because the brachiopod fauna of the Park shale is still largely unknown, it is not now possible to state what factors are responsible for the change noted. The Middle Cambrian brachiopods occur regularly with the trilobite molts, in both shale and limestone. They are rarely broken, but their small size and the large percentage of chitin in their shells may permit a certain amount of transportation without damage. Such a feature is suggested in the early Upper Cambrian assemblages where the small undamaged neotreme species occur with broken shells of the larger, more calcareous shells of Lingulella and Dicellomus. The many-layered shell of Dicellomus is probably rather susceptible to breakage, but great numbers of comminuted shells are found in the coquina nodules of the lower Pilgrim beds, the nodules clearly representing piles of organic debris. In sand deposits also the shells are sorted and broken. I believe that this form, at least, lived on the sandy hard-bottoms not too far off shore. Apparently the genus needed the presence of land debris for its maximum development, since its numbers in near-shore sands are much greater than in limestones, such as those developed on the western platform, where a much smaller number of specimens has been obtained. In the Conaspis zone of the Franconian stage, the two articulate brachiopods Eoorthis and Billingsella produce widespread "reefs" or meadows in the western platform area and in Wyoming eastward across the state. Eoorthis, appearing first, established itself on the relatively hard bottom of the Collenia magna algal meadows and persisted there only so long as the water was clear and shallow. All through the silt and pebble conglomerates of northeastern Montana and into Wyoming no such "reef" development has been noted, though occasional shells occur in the debris of the trilobite coquina nodules. The Eoorthis bed is never more than a few inches thick. Later in the Conaspis zone Billingsella produced similar brachiopod meadows over much the same western area, but of somewhat greater thickness. Throughout the rest of the Upper Cambrian the articulate brachiopods are increasingly prominent in the faunas, but until Trempealeau time are not common in northeastern Montana. Such a distribution suggests that all the articulate and most of the inarticulate Cambrian brachiopods favored hard-bottom, well-oxygenated, relatively shallow water habitats.

The Mollusca are very poorly represented in the fossil collections, though actually many of the trails and faecal pellets may well have been produced by either the pelecypods whose shells are unknown, or the gastropods which are only poorly known. Small specimens of Helcionella occur in the Middle Cambrian Meagher limestone. It is not certain whether this form is a true benthonic gastropod, or whether it may be an allied mollusk possibly of semi-planktonic habit, like Hyolithes, shells of which occur rarely throughout all the formations, with local concentration along a bedding plane, indicating stranding and fairly rapid burial. From all the Upper Cambrian beds, only five shells of two genera have been obtained. In the Cambrian of the Mississippi Valley both Hypseloconus and Scaevogyra are prolific members of gastropod biotas clearly adapted to the littoral and sublittoral rough water zones around rocky cliffed shores. It appears probable that this habitat existed at this time to the northeast of the Montana-Wyoming area and only these few shells are found in the fossil debris since they normally were heavier than the other remains and would have had to be transported the farthest. The occurrence of Hypseloconus in beds of Dresbach age has further interest in suggesting the southward migration of the genus along the shore line, since it is not known in the Upper Mississippi Valley faunas until Franconian time. The complete absence of cephalopods throughout this area must probably be attributed to temperature and/or the amount of clastic material which dominated the sedimentation. The class appears in beds of Trempealeau age in the Mississippi Valley and in Alabama wherever dolomite is developed.

The Arthropoda are abundantly represented by the trilobites, but also present is a primitive branchiopod, Crusoia cebes, and the many fragments of merostome tests indicate a good number of primitive Arachnida. The Merostomata are better known from the Upper Mississippi Valley where the local development of fine siltstones favored their preservation. Apparently sedimentation was too slow and sporadic in the Montana-Wyoming area to furnish adequate burial.

Although it is difficult to reconstruct with certainty the habits of a class with no close living relatives, the trilobites were presumably prominent members of a normal Cambrian marine fauna and as such had representatives occupying all available habitats in the epicontinental sea. The majority of the genera in any assemblage appears to have been vagrant benthos, either actively predaceous or bottom scavengers. Zacanthoides, Bathyuriscus, Ehmania, Elrathiella, Tricrepicephalus, Crepicephalus, Ptychaspis, Prosaukia, Dikelocephalus are examples of this group. Genera such as Millardia, Menomoni and Bridgeia, characterized by a narrow, many-segmented, worm-like thorax and stalked or strongly elevated eyes, were probably mud-ingesting forms burrowing in and just beneath the surface ooze. The Agnostida may well have been sessile or nearly sessile benthos, living buried in the bottom ooze without fear of suffocation because of the exceedingly slow rate of sedimentation over this area. From our present knowledge of the trilobite appendage it is difficult to appraise the animals' ability to adapt to a nektonic mode of life and to become strong swimmers. Certainly they could swim short distances above the sea floor. It has been suggested that some genera such as Arapahoia, Kingstonia, Coosia, Pseudolisania, Plethopeltis, and Illaenurus, all characterized by an obsolescence of furrows and smoothing or streamlining of the glabella, and several having large fan-like pygidia, show structura

changes adapted to speed of motion. These genera are admittedly widespread in occurrence but no more so than many genera of quite different structure and presumably benthonic. In trilobites it must be remembered that distribution of adults is certainly in part at least controlled by distribution of the protaspid larvae, whose structure suggests planktonic adaptation. One Cambrian genus, Pemphigaspis[7], appears to have been adapted to a semi-planktonic or planktonic life. The body is short, oval, with genal spines extending laterally, and an oval very swollen pygidium. Its distribution from the Cordilleran to the Appalachian either as rare sporadic individuals or as many specimens in a single horizon in one locality, indicates local stranding of a floating form.

The several algal meadows that developed on the western platform may have represented conditions comparable to a reef environment. However, only in the Collenia magna meadows have we found sporadic disarticulated trilobite remains. The genera and species represented appear to be common widespread Elvinia zone forms, and it is quite possible that the fossils represent only broken molts drifted into the algal meadows by the waves. No trilobite species are yet known which appear particularly adapted to reef habitats. It seems clear, however, from the restricted occurrence of trilobites in the distinctive littoral gastropod assemblages of the Mississippi Valley, that the trilobites kept beyond the reach of surf or strong waves and preferred quieter waters, either relatively shallow depths in protected bays or moderate depths (100-200 feet) off open coasts.

Among the benthonic genera there appear to have been forms specially adapted to each kind of bottom as well as other genera that were equally at home everywhere. Recently it has been possible to show that Albertella, Zacanthoides, Anoria and Bathyuriscus favored a soft silt bottom. In the late Upper Cambrian the large Dikelocephalids seem to be restricted to a siltstone facies but this may be a feature of preservation rather than habitat.

In the Upper Cambrian the peculiar distribution of Arapahoia appears best explained by temperature control and depth of water. The genus occurs in shales and limestones in southwestern Newfoundland, and all the way down the Cordilleran area to Arizona, but only one specimen is known in a sand facies in the Black Hills, and it is unknown in the interior of the continent and the rest of the Appalachians.

The Aphelaspis fauna is unique among Upper Cambrian faunas in the small number of genera (5), which occur all over the United States, and the large number of individuals of each species. In modern seas such a faunal assemblage characterizes cool and cold waters. Thus the physical make-up of the Aphelaspis fauna indicates the migration of boreal genera southward as cool currents dominated the interior seas. This event was correlated with the nearly complete extinction of the preceding Crepicephalus fauna. A single

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7/ The correct reconstruction of this genus has recently been made by A. S. Palmer, from specimens found in Minnesota.

genus, Blountia, is common to the two zones, but the species are entirely distinct.

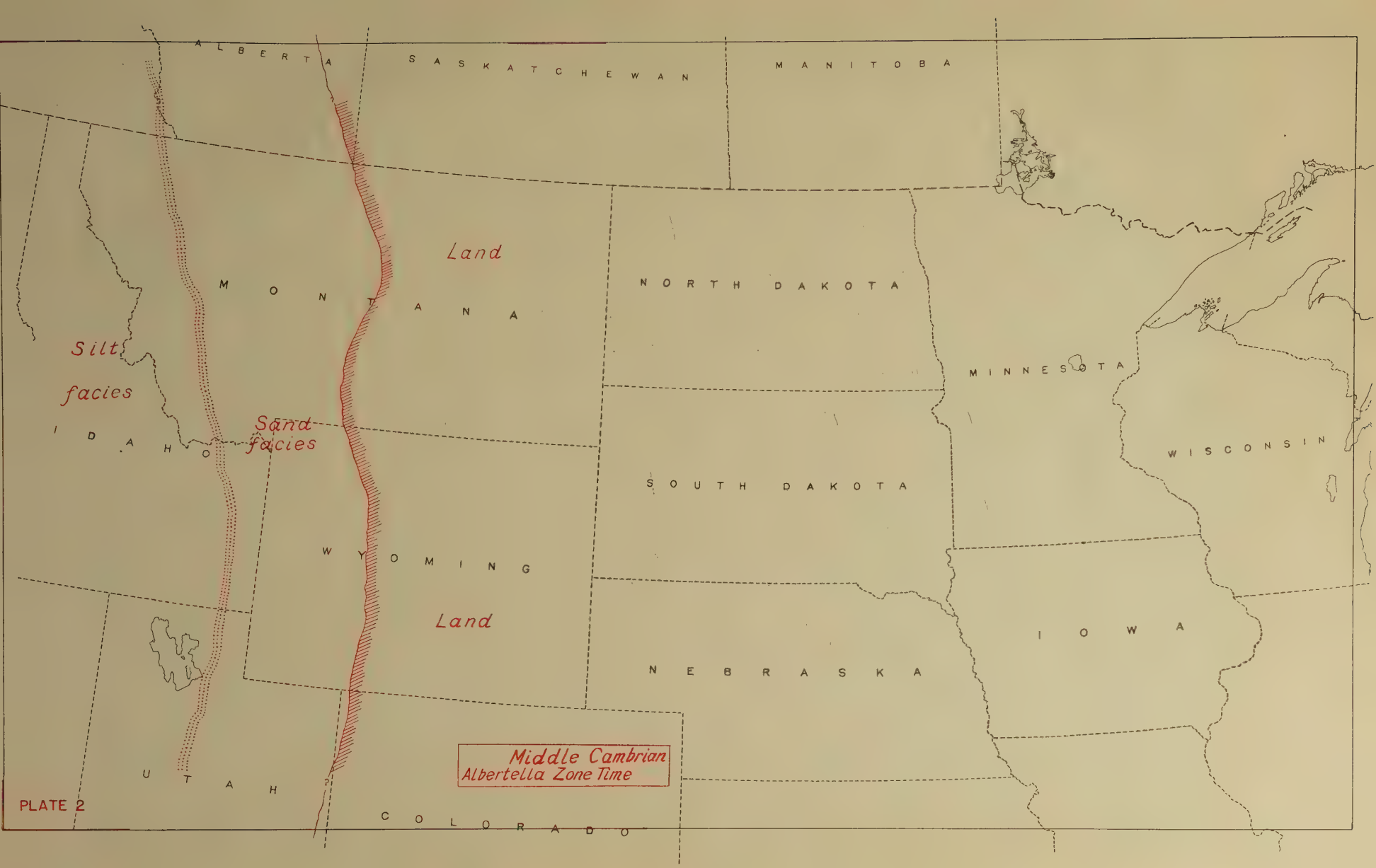
The marine flora of the Cambrian seas seems to be well represented in given areas. Not too much attention has been paid to the calcareous algae in the formations, but there is apparently a definite correlation between their occurrence, the western platform, and a lime facies. Never have any fossil algae been observed in the silt and pebble conglomerate facies of northeastern Montana. Two types of algae are known--one, represented by Tetonophycus in the later Middle Cambrian and by Collenia in the Upper Cambrian produced widespread algal meadows through northwestern Wyoming and adjoining portions of Montana. During the time between the development of these meadows there flourished in the shallow waters over this same area, another type of alga, Aulophycus, a prolific, non-"reef" forming, small twig-like plant. It is assumed that the "reef" types developed in relatively clear water when the shallow sea floor was stable for an appreciable length of time. It is interesting that in both occurrences they appear when or shortly after the dominant facies of the area has changed from a lime to the silt and pebble conglomerate facies. In contrast, Aulophycus seems to have flourished in clear waters on a very slowly sinking shallow sea floor.

THE FACIES AND THEIR ECOLOGICAL IMPLICATIONS

As mapping in this region has been done generally on a two mile to the inch scale, the recognized formations are the major lithic units, and the litho-facies of the area may be discussed in these terms. Because of incomplete knowledge of the faunas, it has been common practice to correlate the formations on the basis of lithology. In Montana where the faunas are best known, this method is satisfactory through the Meagher limestone, but the heterogeneity of the succeeding beds has led to many errors in interpretation when the fossils are not considered. In Wyoming the faunas are practically unknown, and the correlations given are tentative.

No Lower Cambrian is known in the entire shelf area. In the north, Lower Cambrian sediments are restricted to the Cordilleran geosyncline proper. To the south and west in the miogeosyncline of Utah some portions of the excessively thick basal Brigham quartzite may be Lower Cambrian (Williams, 1948).

The downwarping of the shelf area and initial encroachment of the Middle Cambrian sea was relatively rapid and widespread during Albertella zone time (Pl. 2). In Montana the shore position or positions are not known, as their probable sites are now deeply buried. In Wyoming, after the initial rapid spread of the sea, the northwestern shore of Siouxia was gradually inundated until Elrathiella zone time (Pl. 3). After this time downwarping slowed to a halt, the shore line was stabilized, (Pl. 4) and the sea floor became progressively shallower until the beginning of Upper Cambrian time. For the Middle Cambrian the same facies in the same stratigraphic succession can be readily recognized over nearly the entire area, the formational units changing thickness from west to east depending upon the dominance of the lime or the silt facies.


ALBERTA
SASKATCHEWAN
MANITOBA
MONTANA
Land
NORTH DAKOTA
MINNESOTA
Silt
facies
Sand
facies
IDAHO
WISCONSIN
SOUTH DAKOTA
WYOMING
Land
IOWA
NEBRASKA
Middle Cambrian
Albertella Zone Time
UTAH
COLORADO
PLATE 2

The succession begins everywhere with a basal sandstone or quartzite, the Flathead. Often a basal conglomerate of poorly sorted quartz pebbles with feldspar is locally prominent. Dominantly, the formation consists of coarse-to fine-grained quartz sands, commonly cross-bedded. Thin micaceous shales and an oolitic hematite sandstone appear near the top. No fossils are known except a few undetermined inarticulate brachiopods. Deposition took place probably during Albertella zone time because the Flathead conformably underlies the Wolsey and Gordon shales, formations which carry faunas of the Glossopleura-Kootenia zone.

It is generally agreed that the shales overlying the Flathead represent the gradual transition of the shelf area from a sand to a silt facies. Three names are applied to this shale unit, the Gordon in northwestern Montana, the Wolsey in central and southern Montana, and the lower shale member of the Gros Ventre formation in Wyoming. Throughout this area the shales are remarkably uniform and lithologically distinct. In the lower third, are highly ferruginous sandy shales of a distinctive yellow-green coloring. The beds are thin with irregular surfaces marked by worm trails and borings, tracks, cross ripple-marks and numerous vague streaks and bands. In the middle and upper parts of the formation, fissile micaceous (both chlorite and sericite) shales are prominent. Chlorite is abundant throughout and appears responsible for the characteristic dark green hue of the shales. Glauconite is present both in the basal sandy and the upper calcareous beds. Gray to gray-green limestone lenses, a few inches to several feet in size, and crowded with inarticulate brachiopods and disarticulated trilobite carapaces, are common in the upper half. These shales represent the obviously slow, but persistent accumulation of fine silts derived from a land mass upon which metamorphic and igneous rocks were exposed. Toward the end of this time the trilobites and brachiopods became so abundant that their remains formed appreciable current-sorted piles of debris in local hollows on the muddy bottom. The time of deposition is adequately dated by fossils in Montana, but is based solely on lithologic composition in Wyoming.

A limestone or limestone series conformably overlies these shales in all exposed sections of Montana and in the western half of Wyoming. The limestones vary considerably in thickness and lithologic detail from locality to locality, and the thicker sections also appear to cover a longer time. In northwestern Montana, in a region that lay possibly partly within the miogeosyncline, Deiss measured a sequence of oolitic to fine-grained limestone and arenaceous to calcareous fissile shale, ranging in thickness from 1354 feet in the southwesternmost section, to 973 feet in the northeasternmost. The formations were named in ascending order, the Damnation, the Dearborn, the Pagoda, the Pentagon and the Steamboat. The fauna of the Damnation belongs to the Glossopleura-Kootenia zone, indicating that lime deposition began in this area while a silt facies was dominant elsewhere. The oolitic character of the limestone indicates that intermittently the water was clear of silt, but extremely shallow. The thickness of the limestone may be explained by deposition on a relatively shallow sea floor that subsided slowly but steadily during the entire time. Silts were carried intermittently into the area by currents, and each of Deiss's formations is delimited so that the base represents a time of major silt influx. Since Anomalocephalus

ornatus Deiss and several species of Elrathina and Ehmania are known from the Meagher of southern Montana, the Pentagon shale cannot be interpreted as a time wedge (Deiss, 1939, p. 43), but clearly represents a transition phase into the silt facies toward the Laurentian shoreline lying off to the northeast. The Steamboat limestone is represented entirely in the eastern areas by shale referred to the Park formation. In central and southern Montana a single limestone unit, the Meagher, is recognized, ranging in thickness from 374 feet in the Beaver Creek section[8/] to a two foot limestone in the Little Rocky Mountains which carries a basal Elrathiella fauna. This bed appears to represent about the northeastern limit of the lime facies in Montana, and indicates the time of maximum downwarping of the shelf area. Later the silt facies gradually re-established itself farther and farther westward. In central Montana the Meagher is conspicuously tripartite--with a basal limestone, a middle calcareous shale and an upper limestone unit, all three thinning to the east. The limestones are fine-grained, light gray to black, with many argillaceous seams and partings, and several beds contain a few small well rounded limestone pebbles, a type characteristic of off-shore deposits (McKee 1945). The same three divisions carry through southern Montana and into Wyoming where they are known as the Death Canyon member of the Gros Ventre formation, ranging in thickness from 300-350 feet in the westernmost sections to nothing somewhere near the center of the Owl Creek Mountains (Miller, 1936b, p. 123). Thus the eastern limit of the lime facies is more exactly known in Wyoming.

After the maximum downwarping of the shelf area at the beginning of Elrathiella zone time, there was no further movement over the eastern and central portions of the shelf, but the western portion and border continued to sink slowly during all of Elrathiella zone time and possibly until a little later (the faunas of these upper parts are not well enough known to date this horizon exactly). Thus in the western portions, considerable thicknesses of limestone are the time equivalents of thinner limestone sequences in the central portions and deposits of shale and sand in the east. At this time also the shoreline was established in eastern Wyoming (Pl. 3) and remained near this position for the rest of Middle Cambrian time.

Deposition in eastern Wyoming, as exemplified by sections from Wind River Canyon to the eastern side of the Bighorn Mountains, began probably near the beginning of Elrathiella zone time, and beds of this age form the lower part of the Deadass formation, a monotonous and indivisible series of sands and shales becoming more calcareous at the top. The type section in the Wind River Canyon contains approximately 60 feet of Upper Cambrian beds at the top (Miller, 1936b, p. 136), but the remaining 567 feet are characteristic of the deposits laid down in this eastern region during the upper half

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8/ The 911 foot limestone sequence of the Helena district cannot be considered in normal east-west transition with these central Montana sections, because it was originally deposited in far southwestern Montana (Lochman and Duncan, 1944, p. 17) and as Deiss observed (1936, p. 1308) is lithologically more related to the northwestern Montana sequence.

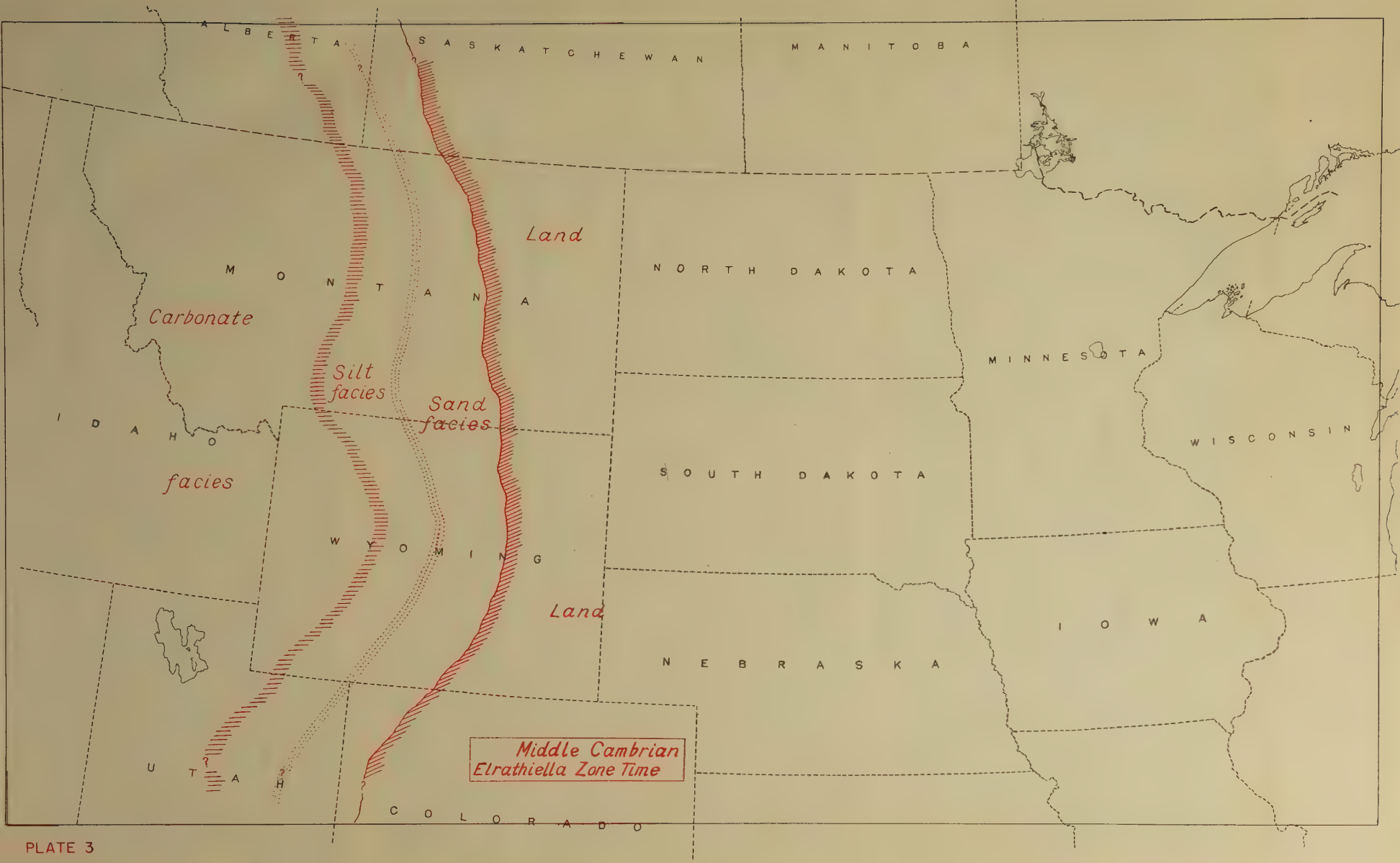

ALBERTA
SASKATCHEWAN
MANITOBA
Land
MONTANA
NORTH DAKOTA
Carbonate
facies
Silt
facies
Sand
facies
MINNESOTA
IDAHO
facies
WISCONSIN
SOUTH DAKOTA
WYOMING
Land
IOWA
NEBRASKA
Middle Cambrian
Elrathiella Zone Time
UTAH
COLORADO

PLATE 3

of Middle Cambrian time. The lower 50 feet are the sands of the transgressing littoral zone. The succeeding fine sands and shales, with certain horizons riddled by Scolithus tubes and covered by tracks, trails and ripple marks, were deposited slowly over extensive shallow flats. In the upper half of the formation glauconite is prominent, and first a silt, then a silt and pebble conglomerate facies become dominant over the area. The contained fauna of the upper beds, including the cited "Glyphaspis"-like trilobite, is the only fauna now known in the formation and is of late Middle Cambrian age. The same fauna occurs in the upper shale member of the Gros Ventre formation in western Wyoming. Farther east in Shell Canyon, a typical section of the Bighorn Mountains, the clastic percentage is high but all facies of typical shallow water deposition are present. Beds of yellow and white sandstone, gray green fissile shales, coarse red sandstone and maroon shales, and an occasional thin white arenaceous micaceous limestone, alternate repeatedly, and there is a 50-foot massive yellow sandstone near the middle of the sequence. Near the top of this sandstone is a 3-foot bed of intraformational conglomerate composed of slabs of a dark brown sandstone.

After Elrathiella zone time in the eastern and central portions of the shelf area and probably somewhat later in the western portions, the westward spreading silt facies became dominant. It is assumed that the major cause for this change was the cessation of downwarping of the western portion of the shelf, since the Tetonophycus meadows of the western Wyoming sections appear at the top of the Death Canyon or near the base of the succeeding upper shales. In northwestern Montana comparable algal structures are recorded in the lower 40 feet of the Steamboat limestone. The algal meadows seem to have about the same general position in time, but apparently developed as local patches. It is generally assumed that they grow best in relatively shallow water, 15 feet or less. In central and southern Montana and Wyoming the sporadic appearance of strong currents bringing silt from the east was an important factor in ending the limestone deposition. In the Crowfoot Ridge section, the Tetonophycus meadow occurs as the top of the Meagher and is overwhelmed by the initial silts of the Park shale; in the Death Canyon (Blackwelder, 1915) and Sheep Mountain sections, Tetonophycus overlies 50 feet or more of shale, but after an accumulation of only a foot or so of lime, the meadow was destroyed by another influx of silt. However, in the Chinese Wall section in northwestern Montana, the algal meadows are underlain by limestone, in part oolitic, and overlain by intercalated shale and limestone, some of it conglomeratic.

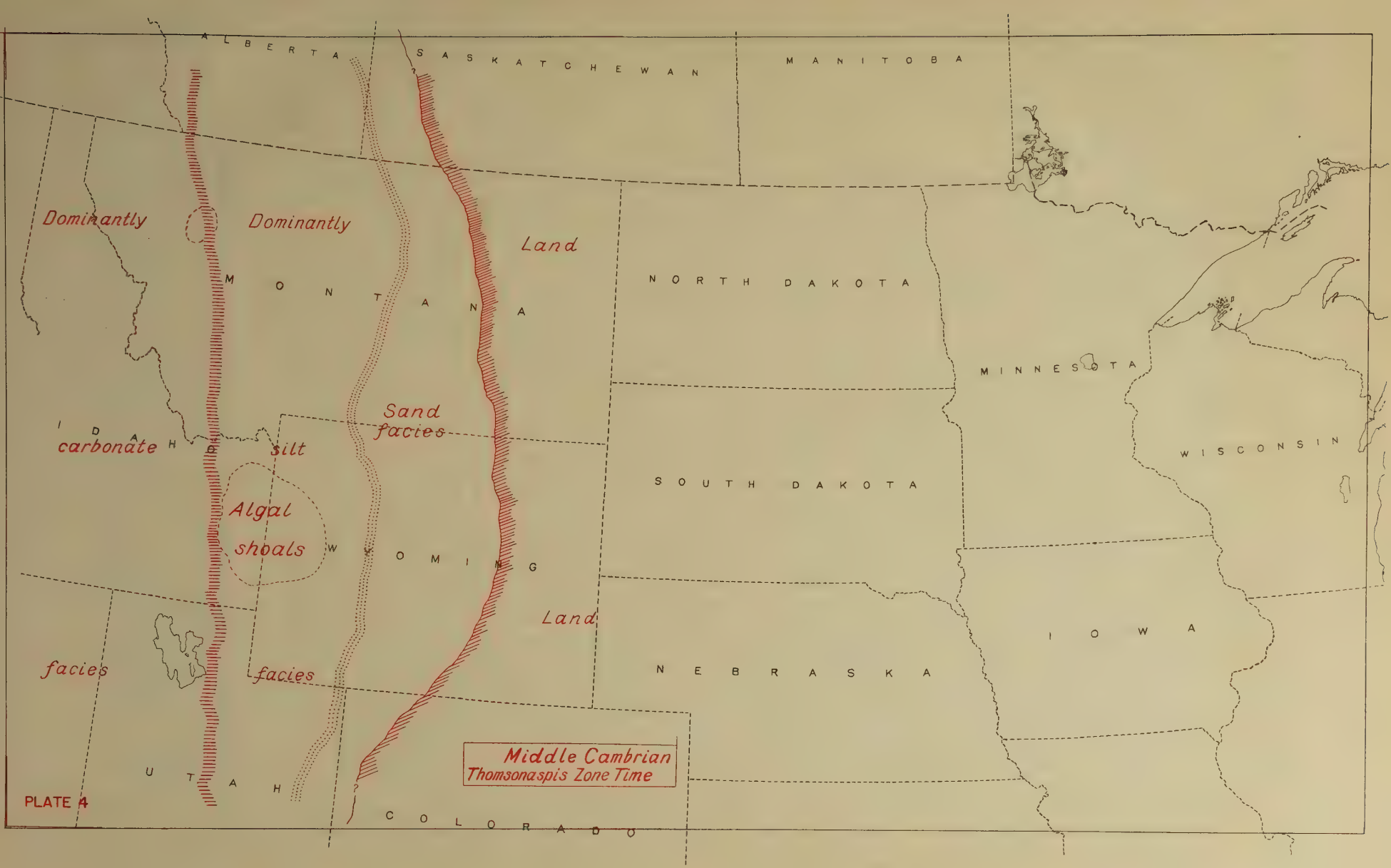
The youngest Middle Cambrian beds throughout the area are characterized by the dominance of arenaceous shale and near the top an abundance of flat pebble limestone conglomerate. Although their fossils are the least well known of any Cambrian faunas in this region, several faunal zones have been tentatively recognized, and from them it appears that these beds in the eastern and central portion represent a somewhat greater length of time, starting earlier, than the beds in the western portion, where the earlier faunas lie in the limestone facies. The exact thickness of the unit is highly variable, and seems to be without significance. In northwestern Montana the unit is the Switchback shale. This formation is a series of intercalated calcareous, arenaceous shales and limestones, with rounded flat pebble conglomerates throughout the section and a few edgewise conglomerates at the

top. In central and southern Montana it is known as the Park shale and in Wyoming as the upper shale member of the Gros Ventre formation. An initial dominance of the silt facies, was followed over the entire area by a steady fluctuation between conditions of clear, relatively quiet water and those of strong turbulent currents. Limestone nodules of trilobite and brachiopod coquina scattered through the shale are conspicuous. Thin beds and lenses of argillaceous limestone pass laterally into shales; thicker beds, 3-5 inches, are composed of a crystalline, often fossiliferous, glauconitic limestone matrix cementing a moderate number of small well rounded pebbles 1-1½ inches in diameter, 90 percent of which lie parallel to the bedding planes. These pebbles clearly represent broken up pieces of the thin limestone beds, and have apparently been moved about on the bottom by currents and waves for an appreciable time and possibly distance before their ultimate deposition. The lime content of the unit becomes somewhat higher in the western part of the area simply by an increase in the thickness of the individual limestone beds and lenses in the upper part. Locally, as at Nixon Gulch, the limestone and limestone pebble conglomerates reach a thickness of 6 feet and form a noticeable low cliff in the outcrop.

It is now recognized that the placing of the Middle-Upper Cambrian time boundary must be arbitrary throughout this region, as neither a lithologic nor a sharp faunal break are evident. The same physical conditions continued over most of the shelf, with the shallow waters alternately calm and clear and rough and muddy. In the Shell Canyon section, I found the first appearance of an early Cedaria fauna occurring above a conspicuous one foot layer of bright red sandstone. This sandstone lay at the top of 10 feet of sandy beds succeeding limy shales and limestones carrying a Middle Cambrian fauna. It is interesting to note that at least in this section where the lithology has been examined in detail, there is a strong suggestion of gradual shallowing and probable subaerial exposure of the shelf for a short time. But it is essential that fossils be considered with the lithology since a 3-foot bed of a similar coarse bright red sandstone was observed in the same section at least 175 feet lower.

The criterion for the base of the standard American Upper Cambrian was the time of initial Cambrian marine sedimentation in the interior of the continent; and the genera and species found in the lowest fossiliferous beds were regarded as the oldest Upper Cambrian fauna--the Cedaria zone. The faunal sequence as it was worked out in the upper Mississippi Valley thus became the standard Upper Cambrian succession. However, in the Montana-Wyoming shelf area as well as farther west in the miogeosyncline and the Cordilleran eugeosyncline, the physical conditions remained unchanged during this time and the earliest genera of the Cedaria fauna mingled with genera which had already been in the region for some time during the late Middle Cambrian (Lochman and Duncan, 1944, p. 37-38).

During early Upper Cambrian, the area remained essentially an extensive shallowly submerged shelf; an almost imperceptible downwarping of the shelf was associated with the gradual downwarping of the interior to the east and the seas were finally permitted to reach the Mississippi Valley region before the end of Cedaria time. In most of Montana and Wyoming this negative movement was so slight that gross physical conditions were unchanged, though


ALBERTA
SASKATCHEWAN
MANITOBA
Dominantly
Dominantly
Land
MONTANA
NORTH DAKOTA
MINNESOTA
Sand
facies
IDAHO
carbonate
silt
WISCONSIN
SOUTH DAKOTA
Algal
shoals
WYOMING
Land
IOWA
facies
facies
NEBRASKA
Middle Cambrian
Thomsonaspis Zone Time
UTAH
COLORADO
PLATE 4

shallowness and turbulence of the water seemed more marked. In the sections of southwestern Montana and western Wyoming silt deposition ceased, and silt formed only seams between the beds of oolitic and flat pebble conglomerate limestones. Over the greater part of the shelf area, a clearer water condition is predicated by the increased development of thin silty limestones in the shales. Fissile gray-green shales and thin dense limestones alternate now with much thicker lenses and masses of pebble conglomerates, the fragments 4-6 inches in length. The small, rounded flat pebble conglomerate characteristic of the preceding beds is inconspicuous or absent, and edgewise conglomerate is dominant. This type has also been termed "breccia conglomerates" (Deiss, 1939) and "intraformational breccia" (Miller, 1936b). The fragments are angular, obviously broken-up beds of the thin limestones into which they may be traced. The fragments lie at every angle and the matrix is often shaly and dense, with scattered patches of organic debris. This coquina is usually associated with the conglomerates and only very rarely occurs as isolated nodules among the shales as in the underlying Park. The thicker masses of pebble conglomerate cause the Upper Cambrian beds to form a steeper slope with more low outcrops than the underlying shales (Dorf and Lochman, 1940, p. 549, pl. 4). Toward the end of Cedaria zone time, as a result of the eastward transgression of the shoreline, silt reached the western edge infrequently and calcareous algae, Collenia spissa, were locally developed along it. In Wyoming the Cedaria zone beds are commonly placed in the upper shale member of the Gros Ventre formation since careful study of the lithologic distinctions have not been made and the beds occur in the outcrop as a slope similar to the underlying Middle Cambrian beds. When more detailed work is done it will be possible to pick out the Upper Cambrian beds on the basis of lithologic composition as well as fauna (Miller, 1936b, p. 123). These Upper Cambrian beds are a part of the Boysen formation (Deiss, 1938, p. 1091-1101) and I have so placed them on Plate 1 wherever I had sufficient faunal information. In the Pryor Mountains and the Bighorns, these beds as well as all the succeeding Upper Cambrian are part of the indivisible series now called the Deadwood formation (Meyerhoff and Lochman, 1938). In extreme northwestern Wyoming and south and central Montana including the Horseshoe Hills, the beds are referred to the lower member of the Maurice formation. In central and northeastern Montana they form an indivisible lower part of the shale and pebble conglomerates of the Pilgrim formation. In southwestern Montana the lithologic composition of the beds has changed from shale and edgewise pebble conglomerates to dominantely oolitic and flat pebble conglomerate limestones with shaly seams and form an inseparable basal portion of the Hasmark formation. A similar lithologic change seems to occur in the Wyoming sections from Sheep Mountain west, but the faunas are not too well known. However, the limestones are always placed in the Boysen formation (Foster, 1947). In northwestern Montana, the beds if pressent must also . have been dominantly limestone and are now represented in the basal portion of the Devils Glen dolomite.

It is obvious when dealing with these early Upper Cambrian beds that the standard Middle-Upper Cambrian time boundary in this shelf area does not coincide with the roughly recognized facies and formation boundaries in the area, but cuts across them. Consequently, the Middle-Upper Cambrian boundary as it has been and still is recognized by field geologists in the area is a facies boundary which is much older in the western portion of the region than in the east.

The transgression of the Upper Cambrian seas appears to have been relatively rapid. The northern shore of Siouxia was south of the Black Hills by the middle Cedaria subzone, and by late Cedaria time much of the basal transgressive sandstone had been deposited over the Mississippi Valley region and the characteristic lithofacies of the Dresbach had become established. Numerous scattered islands are known along the northeastern and eastern shore of Siouxia as far as the St. Francois Mountains. Several known islands off the southern Laurentian shore are shown in Pl. 5, and it is probable that many more existed along the entire western shore, but both subsequent erosion and present concealment render conditions in this area conjectured. All this interior region is essentially nothing more than a greatly expanded shelf area, the descendant of the Montana-Wyoming shelf of the Middle Cambrian. The facies belts are correspondingly much broader and most significant in their distribution. A transgressive sand facies developed first over the interior region. During the later Dresbach the sand facies became dominant and permanent over most of the Dakotas, Minnesota and Wisconsin. To the south this facies passed directly into a sand-carbonate facies with no intervening dominant silt facies. The Missouri Cambrian is dominantly a dolomite and limestone series though shales appear locally in several formations. However, the carbonates do contain an appreciable percentage of fine silt and clay, revealed when the carbonates are dissolved. The situation suggests that 1) the streams of southern and southwestern Laurentia were relatively short, with a small watershed; 2) the limited amounts of sand and silt were widely spread and reworked over the interior shelf, and the finer silts and clays slowly drifting southward but were too thinly spread to dominate the facies very long at any one place; 3) after the initial transgression Siouxia and the surrounding islands were furnishing only small amounts of sand and silt which settled primarily in the littoral and sub-littoral regions. The persistent position of the silt and pebble conglomerate facies over northeastern Montana and adjoining corner of Wyoming suggests that the mouth of a major river system was located on the northwest coast of Laurentia. It is unfortunate that we do not know the western shoreline of Laurentia in sufficient detail to accurately locate the debouchure. However, both the distribution of the lithofacies of the Middle and Upper Cambrian sediments (Krumbein, 1948, p. 1914, fig. 3), and of the Upper Cambrian trilobite genera indicate the presence of southward moving currents. These currents brought large amounts of mud and silt into the Montana-Wyoming shelf area. The sections of the Black Hills show particularly rapid variations in facies both vertically and horizontally and appear to have lain until after Conaspis time at the focal point of all three facies types. The Black Hills must also have been under the influence of the sand facies bordering the northern and western shores of Siouxia.

In the later two-thirds of the Dresbachian stage, Crepicephalus and Aphelaspis zone time, Upper Cambrian seas reached maximum transgressive conditions in the Montana-Wyoming region as well as in the interior of the continent. Limestones are dominant in the western halves of both states, and in Montana the western edge of the shelf area again sank slowly and persistently during the entire time. In northwestern Montana the Devils Glen dolomite should contain beds of this age. In west-central and southwestern Montana the Hasmark is a dark gray crystalline limestone, characterized by

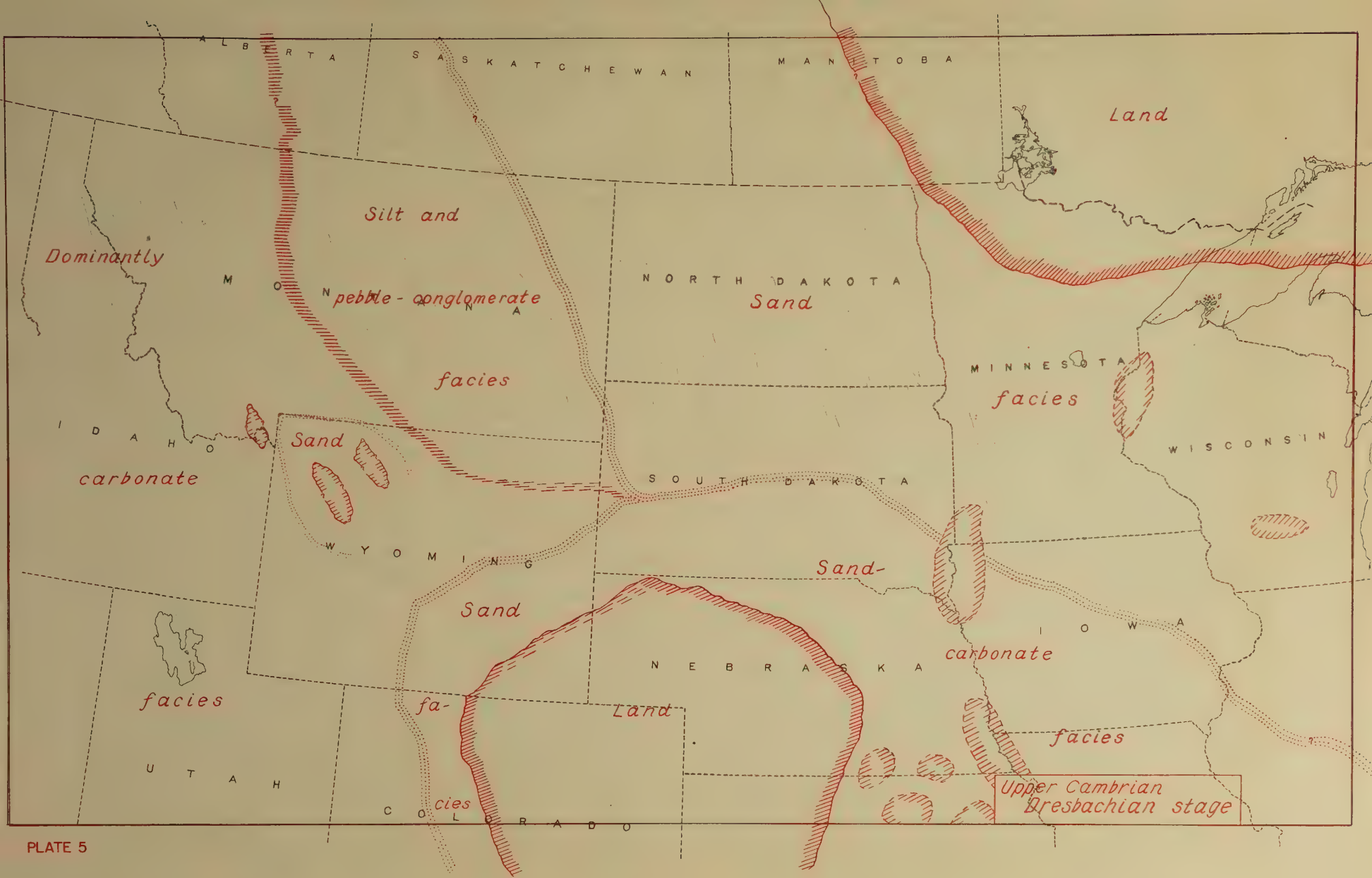

ALBERTA
SASKATCHEWAN
MANITOBA
Land
Silt and
pebble-conglomerate
facies
Dominantly
carbonate
facies
MONTANA
NORTH DAKOTA
Sand
MINNESOTA
facies
WISCONSIN
IDAHO
Sand
SOUTH DAKOTA
WYOMING
Sand-
carbonate
Sand
facies
IOWA
NEBRASKA
fa-
cies
Land
facies
UTAH
COLORADO
Upper Cambrian
Dresbachian stage

PLATE 5

an abundance of oolites and twig-like algae, Aulophycus, and some small flat pebble conglomerates. Locally, it attains a thickness of 1000 feet. From the Horseshoe Hills to the northwestern edge of Wyoming, limestones of the same age and comparable lithology belong to the upper member of the Maurice formation. This unit decreases in thickness from 250 feet in the north at the Horseshoe Hills to 100 feet in the south at the North Grove Creek section and 60 feet on Crowfoot Ridge. South of Yellowstone National Park, beds of this age are a part of the Boysen formation. They are oolitic mottled crystalline limestones with small flat pebble conglomerate beds which cannot be separated from those of the Cedaria zone except by the fauna. From the Beartooth Butte and North Grove Creek sections south to the Sheep Mountain section (Richmond, 1945), sand is conspicuous in the beds near the top of the Crepicephalus zone. In the northern sections, the beds are an arenaceous limestone with mud-cracked and ripple-marked surfaces, while in the Sheep Mountain section, a real sandstone is developed, an erosion surface is present and all the Aphelaspis zone is missing. A large portion of the northwestern Wyoming shelf area was either above sea or at tide level. The presence of quartz sands in this location and position in the section leads me to believe that the positive movement indicated in the sediments was associated with the uplift of fault blocks of Pre-Cambrian crystalline rocks. From the Warm Springs Creek section (Miller, 1936b) eastward to the Bridger Mountains, the oolitic crystalline limestones and flat pebble conglomerates of this age form a low persistent cliff on the outcrop and were called the Du Noir member by Miller. They thin gradually eastward, but in the Wind River Canyon section the Aphelaspis zone is still present as a thin bed at the top.

During the Dresbachian in central and northeastern Montana and eastern Wyoming the deposition of shales, thin gray limestones and pebble conglomerates continued without interruption. In northeastern Montana, in the Little Rocky Mountains, the shale content is dominant and the lime frequently appears as nodules of coquina. In Montana the beds are an indivisible part of the Pilgrim formation. To the south, the shales become finer and lighter gray in color and in the Pryor and Bighorn Mountains, such shales intercalated with lime nodules, sandy limestones and edgewise pebble conglomerates form the lower portion of the Deadwood formation.

Throughout the entire United States there is evidence of marked uplift of all the shelf areas toward the end of Dresbach time. In the northern and southern ends of the Mississippi Valley, the deposition of marine sands is succeeded by a deposit of non-marine sands, and in Missouri the Bonneterre dolomite is overlain abruptly by the calcareous shales of the basal Davis formation. In the eastern part of the Montana-Wyoming shelf area, no striking lithologic change is apparent, but this part of the section is dominantly sandy shales. However, in the western portions where the lime facies had existed, there is an abrupt change to a series of sands, or sandy shales. But only in a few sections in the northern Wind River Mountains is there physical evidence of a break. This was the most significant movement in this region since the early part of the Middle Cambrian. It initiated regressive conditions which persisted over the shelf area from Franconian time until the end of the Beekmantown. In Montana from the westernmost known sections to the Little Rocky Mountains, the beds of Franconian age consist of intercalated

sandy shales, shales, limestone nodules, thin beds of gray limestone and pebble conglomerates. From Helena west these beds comprise the Red Lion formation; in central and eastern Montana they are the middle third of the Pilgrim formation. In the western sections there is a higher percentage of lime and the beds of pebble conglomerate contain well-rounded disc pebbles, most of them oriented parallel to the bedding plane; in the eastern sections the large angular edgewise pebble conglomerates dominate. This is especially noticeable in the Ptychaspis-Prosaukia zone when the seas were clearer and a minimum of silt was being deposited. As a result, a low cliff, 8-15 feet, of pebble conglomerate developed over the entire area. In the Little Rocky Mountains (Lochman, in press) this cliff consists entirely of coarse edgewise pebble conglomerates with a highly argillaceous matrix; but in the Red Lion formation the small flat pebbles have a crystalline limestone matrix. Several other small lithologic units within these Franconian beds should be mentioned. At the base of the formation is, uniformly, a series of sands or sandy shales, from 30 to as much as 80 feet thick, in which there is no lime development. From the Horseshoe Hills at least to the Teton Range, at approximately 40-90 feet above the base of the formation, the "columnar limestone", a 5-15 foot cliff, represents the algal meadows produced by Collenia magna. These meadows are known to be the same age as everywhere they occur at the top of the Elvinia zone (including the Ptychopleurites subzone). In their striking appearance they are a useful stratigraphic unit to the field geologist, and are besides a valuable ecologic unit to the paleontologist.

From the Horsehoe Hills south into northwestern Wyoming the Franconian beds have been named the Snowy Range formation (Dorf and Lochman, 1940). The same units and lithology persist throughout the region. In west and central Wyoming they are included in the Boysen formation. In the Teton, Gros Ventre, Hoback and northwestern Wind River Ranges, all beds younger than the Conaspis zone are missing and the maximum thickness of the unit is about 80 feet. The absence of the beds is due to post Beekmantown erosion, and it is believed that a full sequence of Cambrian and early Ordovician beds were originally deposited through the area. Along the eastern side of the Wind River Range, beds of the Ptychaspis-Prosaukia zone are present, and farther east in the Wind River Canyon section the entire Franconian appears to be present. In the Pryor and Bighorn Mountains, it is believed that beds of Franconian age form the middle part of the Deadwood formation, but practically nothing is yet known specifically about the faunas or the lithology of these beds.

The last facies chart, Pl. 6, shows the facies distribution of the Franconian, but this chart may also be used for the Trempealeauian since the major facies distribution remained unchanged through the Trempealeau and for the Montana-Wyoming shelf area even through the Lower Ordovician. The amount of clastic material available for deposition fell off markedly, and the lime content of the intercalated shales and pebble conglomerates increased. The shelf remained stable throughout so that no appreciable thickness of beds could be deposited. The small amount of silt available must have been reworked and reworked as the pebbles in the conglomerate are well rounded, often with a hole worn in the middle and coated with glauconite. Locally, as in the Beartooth Butte section, fine dolomitic siltstones are developed.

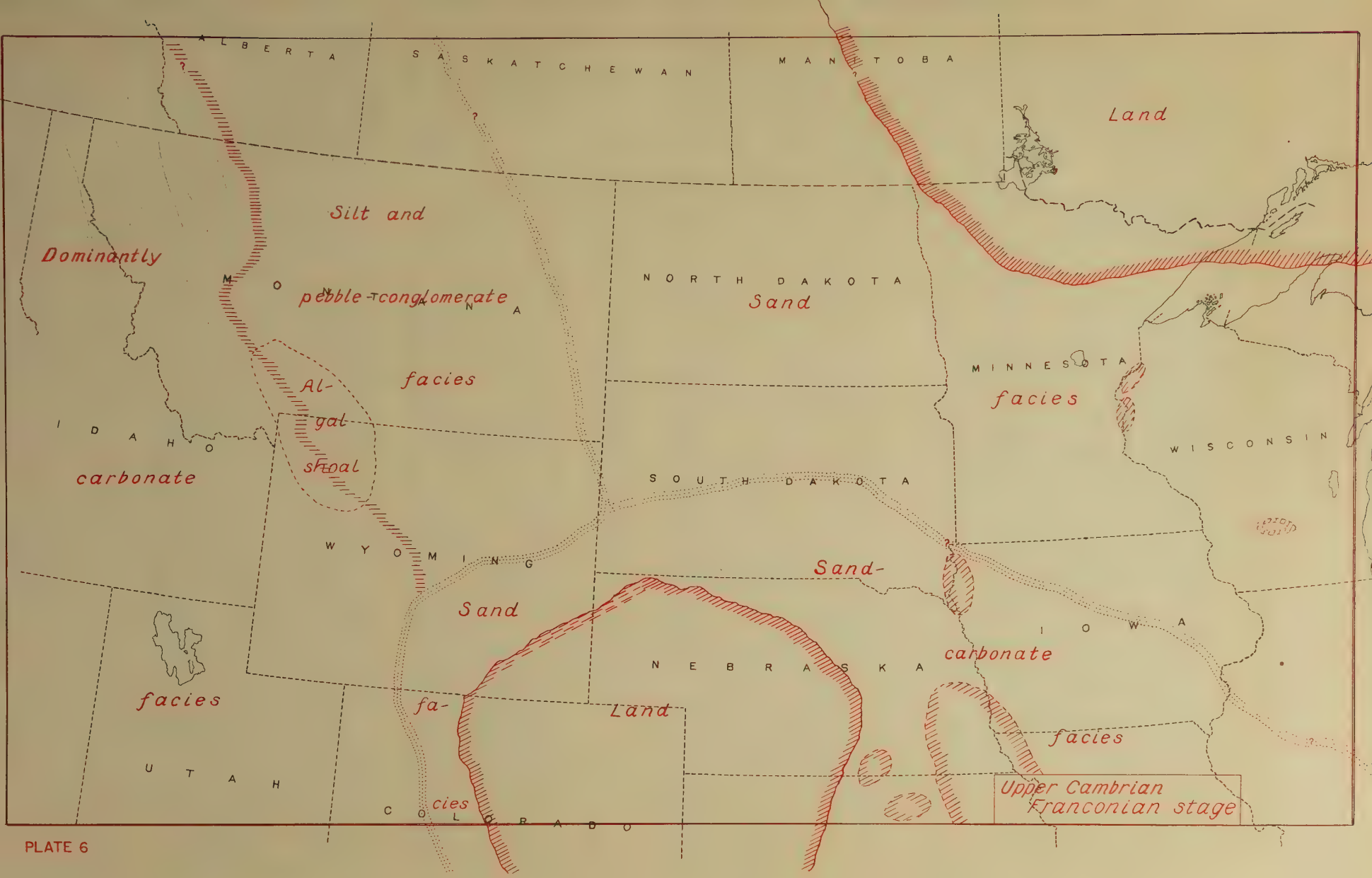

ALBERTA
SASKATCHEWAN
MANITOBA
Land
Silt and
pebble-conglomerate
facies
Dominantly
carbonate
facies
Al-
gal
shoal
NORTH DAKOTA
Sand
MINNESOTA
facies
WISCONSIN
IDAHO
SOUTH DAKOTA
WYOMING
Sand-
Sand
IOWA
carbonate
NEBRASKA
facies
fa-
cies
Land
facies
UTAH
COLORADO
Upper Cambrian
Franconian stage

PLATE 6

It is practically impossible to estimate the original thickness of the Trempealeau deposits. In all the western half of the area they are known to have been partially or wholly eroded; whereas in the Half Moon Pass section, where they are overlain by Lower Ordovician beds, the Trempealeau portion of the section is covered and the fossil zones could not be determined in it. It appears that 80-100 feet would be on the generous side. There is no evidence for either the presence or absence of Trempealeauian beds in all of western Montana. In central Montana they are known to be absent except in the Half Moon Pass section. South of Livingston, Montana, beds of Trempealeau age appear and are called the Grove Creek formation (Dorf and Lochman, 1940). South of Beartooth Butte through western Wyoming they are absent. In central Wyoming they appear as the top 40 feet of the Boysen formation in the Wind River Canyon section. Their presence is not certainly known in the Pryor and Bighorn Mts. but indirect evidence suggests that they are present in the calcareous sands and shales near the top of the Deadwood formation.

Brief mention must be made of the known Beekmantown sedimentation in this region. A Bellefontia zone fauna occurs in the Upper 35-40 feet of the Pilgrim formation in the Half Moon Pass section, the upper 38 feet of the Deadwood sandstone in the core of Union Oil No. 1 Bull Creek well, Crook County, Wyoming, and the upper 40 feet of the Deadwood formation in Spearfish Canyon, northern Black Hills. These beds and their fauna indicate that physical conditions remained unchanged over the entire Montana-Wyoming shelf at least until after Bellefontia zone time, and that at any given locality the lithofacies of the Upper Cambrian continued to prevail. The post-Cambrian conditions of the area will be discussed in more detail later in the paper.

THE ECOLOGIC SIGNIFICANCE OF PEBBLE CONGLOMERATE, OOLITE AND GLAUCONITE

The Middle and Upper Cambrian formations of the Montana-Wyoming shelf area are characterized by the striking abundance of three secondary facies variants of definite ecologic significance. Pebble conglomerate appears in the Middle Cambrian limestone sequence and becomes increasingly conspicuous until, in the Upper Cambrian sediments it is a prominent component of all three facies. In the Montana-Wyoming deposits there occur at least four distinct types of pebble conglomerates, two of which are known to intergrade.

Type 1. In the Middle Cambrian limestone, thin beds of the conglomerates occur sporadically. The pebbles are small, rarely larger than 1 x 1 x $\frac{1}{4}$ inch, of a fine-grained limestone similar to the matrix, with edges well-rounded, and over 90 percent parallel to the bedding plane and the rest at a low angle. The matrix is far in excess of the volume of the pebbles. The sections are not known in enough detail to determine whether the conglomerates hold a certain horizon, but apparently they are of local development. Their site of deposition was nearly 300 miles west of the position of the Middle Cambrian shoreline. This type seems to be exactly comparable to that observed in the Grand Canyon Middle Cambrian section by McKee.

Type 2. This type of pebble conglomerate appears in the late Middle Cambrian shales and is common throughout all the Upper Cambrian formations. It is developed from western Montana and Wyoming to the Black Hills and has also been observed throughout the Mississippi Valley Upper Cambrian. The pebbles are flattish, but irregularly shaped ovals, discs or oblongs, averaging 3 x 2 x ½ inch; the edges are well-rounded and even the surfaces show some rounding and an occasional light coating of glauconite; of a silty dense limestone with occasional glauconite grains; and half or more than half, parallel to the bedding plane, the rest at various low angles. The matrix is a white or gray crystalline glauconitic limestone or limestone coquina comprising approximately half the volume of the bed. Conglomerates of this type always form separate limestone beds of appreciable lateral extent within the shales. The beds may vary from several inches to a foot or so in thickness and form low ridges on the outcrop. The persistent low cliff of the Ptychaspis-Prosaukia zone is a good example. In eastern Wyoming, the Black Hills and Wisconsin, the pebbles of such conglomerates are similar in size and shape but are composed of a silty calcareous glauconitic sandstone and lie in a calcareous glauconitic sand matrix. A number of the pebbles tend to have flat upper and lower surfaces. This type of conglomerate was obviously deposited at a variable but appreciable distance from the shoreline. The composition of the pebbles indicates that they were deposited as thin beds within the same facies domain in which they were later broken up and then redeposited. Their higher silt content as compared to the matrices suggests that the clay content may have been responsible for the cohesion of the original beds which was sufficient to permit fragmentation. These conglomerates have been deposited anywhere from 100 to 1,500 or more miles from the known Upper Cambrian shoreline.

Type 3. In northwestern Wyoming and southcentral Montana, this type appears only in beds of the Cedaria zone, but in the eastern half of the a area it may be found throughout the Upper Cambrian and is particularly well developed in the northeastern Montana sections. I have called this type the edgewise pebble conglomerate, although Deiss calls it breccia conglomerate, and Miller's term is intraformational breccia. The pebbles are large, averaging 6 x 4 x 1 inch, with angular edges and flat surfaces, and obviously freshly broken up pieces of thin silty dense limestone beds intercalated in the same series; 90-95 percent lie vertically or at high angles to the bedding plane, the 5-10 percent near the bottom resting at low angles. Glauconite may appear as layers in the limestone of the pebbles, but has not been observed as a coating. The silty lime matrix makes up a very small amount of the total volume of the bed, with occasional patches of organic debris forming part of the matrix. The deposits are lens-shaped masses which thicken and thin rapidly between the shales and thin limestones, and, commonly, the thin edge of such a mass can be traced laterally to a limestone bed. This type has also been found to merge into type 2 in which the pebbles are smaller, and more worn and the deposit is a thin bed. The coarse sandstone slab-conglomerate described from the Shell Canyon section seems to be a variant of this type. The lithology of the pebbles of type 3 indicates that they also were originally formed in the facies in which they now occur, but as compared to type 2 their transport has been brief.

Type 4. In the sections of southcentral Montana and adjoining parts of Wyoming this type occurs sporadically in the top of the Snowy Range and fully developed in the lower part of the Grove Creek formation. The pebbles are very well-rounded, smooth discs, some of which have a hole through the center, 1 x 2 x ½ inch, heavily coated with a layer of glauconite or a shiny black-brown varnish, possibly a manganese mineral; of a silty fine limestone with a yellow-stained layer beneath the surface; they lie in a jumbled mass with the separate plates of crinoid stems. Only a small amount of glauconitic white crystalline limestone forms the matrix. The local lenses of type 4 generally can be traced laterally into regular beds composed of type 2 conglomerate. The pebbles have been transported the greatest distance over the sea floor and have later lain a long time exposed to the sea water before their final burial.

Two modes of origin of intraformational conglomerates have been advanced; fragmentation by subaequeous sliding (Grabau, Hadding, Miller) and fragmentation by wave and current action either in the littoral--tidal flats--or the sublittoral areas and deeper (McKee, 1945, for references).

For subaequeous sliding the presence of an appreciable slope on the sea floor is a necessary requisite. It is clear even from our incomplete examination of this region that the Middle Cambrian sea encroached over a region of at least moderate relief, but the development of the pebble conglomerate does not appear until during or near the end of the time of maximum transgression, after a thickness of about 1000 feet of sediments had been deposited in the west and about 300 feet in the east. By this time any initial slopes would have been largely concealed, and only minor broad hollows and irregularities would remain, conditions most unfavorable for subaequeous sliding. In the Dutch East Indies, Kuenen (1943) reports that the Snellius Expedition was unable to find evidence of sliding at any depth on slopes of 15° in strongly seismic areas. It seems improbable that any of the Cambrian pebble conglomerates in the Montana-Wyoming shelf area were formed in this manner.

The probable mode of origin is through fragmentation by waves and currents of previously deposited thin silty limestones and silty sandstones. Since various types of ripple marks, mud cracks, a stranded jelly-fish, worm tubes, tracks and trails, and castings of mud eaters are common throughout the formations (even appearing on the surface of beds of pebble conglomerates), the pebbles must have been deposited in water of a depth favorable for the development of such physiographic and faunal features. The similarity of the lithology of the pebble and the matrix indicates also that the original material of the pebble was deposited and the fragmentation and later deposition took place within the same facies area. Agitation of the bottom sediments by waves is known to extend to depths of 180 feet, though the usual maximum depth is around 100 feet. Ripple phenomena may be more commonly produced by currents than waves, and such current ripple marks are now known to a depth of 2400 feet (Maurice Ewing in report to U. S. Navy Department 1949). Marine worms are very common on tidal flats but can range to depths of several hundred feet. Echinoids and other mud eaters favor shallow depths (to 600 feet) but are known from greater depths. Mud cracks necessarily imply exposure on tidal flats. From all available data it seems probable that Type 1 conglomerate may have been deposited in water depths as great

as 200-300 feet as the small size of the pebbles indicates transport over a long distance, presumably seaward. Type 2 was probably deposited at depth of 75 feet to less, for it grades into Type 3 which offers no evidence of long transport and must have come to rest soon after formation, probably at depths of 10-20 feet. Our lack of knowledge of the configuration of the shoreline and the position of islands and channel straits is a great handicap, since tides can be responsible for wide fluctuations in water depth, and occasional violent storms reaching ordinarily sheltered bays could produce the combination of phenomena observed in these beds. Type 4, with pebbles of a shape commonly observed on beaches, is believed to have been shifted seaward to depths of 50-75 feet and lain there for a long time before ultimate burial. I believe that all evidence indicates that the Montana-Wyoming shelf area was relatively stable during the Cambrian, and though sedimentation was slow and slight, the amount of downwarping was so small that the sea floor was kept built up to or above the profile of equilibrium most of the time all the way from western Wyoming to the upper Mississippi Valley.

McKee's suggestion that intraformational pebble conglomerates are associated with and evidence for a regressive sea is particularly interesting when examined in the light of deposits strictly of the shelf area. McKee's east-west profile runs from the shelf area into the miogeosyncline, and it is at the border between them that he finds the development of the regressive pebble conglomerates in his limestone. A comparable position in the Montana-Wyoming area would lie in western Montana, and Deiss's northwestern Montana sections suggest that a similar relationship might be detected if the limestones were studied in comparable detail. On the shelf area proper, as might be expected, after the initial transgression in each particular region, regressive conditions dominate the sedimentation until the cycle has ended.

Oolites are very conspicuous in the mottled crystalline limestones of the Dresbachian stage in the western half of the area, and have also been reported by Deiss in northwestern Montana in the lower part of the Damnation limestone, the Pagoda and the Steamboat limestones, though they have not been observed in the equivalents farther east,--the Meagher and Death Canyon. The mode of origin has been considered by numerous authors (Hadding, 1941; Pettijohn, 1947; Trask, 1939; Twenhofel, 1939). The consensus of opinion favors the formation of oolites in warm saline waters saturated with calcium carbonate and at depths shallow enough for strong wave action. Hadding finds the oolitic limestones in his sections associated with fragmental limestones, large distinct ripple marks, sands, a definite shallow water fauna, and always the shoreward side of the algal reefs. Hadding believes that the optimum depth for the algal reefs is about 150 feet and that the oolites formed in depths between 90-60 feet and were probably deposited near the site of formation. Although their site of origin must be in the water, oolites may be deposited in littoral or even shore dune sites. The requirement of warm saturated waters over the sea floor substantiates the need of shallow depths indicated by the other evidence.

Glauconite is absent from the transgressive littoral sands of the Flathead and Depass formation in Montana-Wyoming and also from all the Upper Cambrian basal sandstones in the Mississippi Valley, but directly following the initial transgression, it appears in the Cambrian section and continues

to its close, becoming very prominent in the Upper Cambrian beds of the area. It is noted first in the top sands of the Flathead, occurs sparingly and sporadically in the Wolsey (the green color of these shales is due to chlorite not glauconite), and in the overlying limestones, and with increasing abundance in the late Middle and Upper Cambrian. Its distribution is somewhat irregular both vertically and horizontally, and one part of a formation may contain a higher percentage than a lower or higher part of the same formation. In the Upper Cambrian, thin seams of almost pure glauconite are present in the pebbles and in the matrix of the pebble conglomerates.

The origin of glauconite has been considered by many authors, but most recently by Galliher, 1935a, 1935b, 1937; Hadding 1932; Takahashi, 1929, 1939. The present discussion is based primarily upon their findings. Though there are still some apparent disagreements, and several uncertainties, a compilation of the information from these sources shows many points of agreement and suggests that a fairly accurate picture of the conditions of formation of the Cambrian glauconite can be developed.

Character of the water. All sources are agreed that glauconite is always formed in saline waters, most commonly marine.

Original material. Galliher has demonstrated the alteration of biotite to glauconite in Monterey Bay, California. A number of earlier observations, such as that of Murray and Renard that glauconite occurred only off coasts of old granitic and crystalline rocks where no large rivers exist, favor this relationship. Takahashi has observed that faecal mud pellets or grains alter to glauconite. He believes the mother material of the pellets to be "clayey materials or colloidal silica mixed with a little organic matter" (Takahashi, 1939, p. 506). He also has found feldspar, volcanic glass, sponge spicules and pyroxene glauconitized, but reports that the "co-existing micas generally are found intact". However, it is apparent in his original 1929 report that little or no attention was paid in the study to materials other than the glauconitized mud pellets, and the bottom and water conditions under which they occurred. No study was made of the shore rocks, but the presence of a number of granitic islands is mentioned in Setouchi Bay, one of the most important sites of glauconitization. Moreover, it should be noted that biotite, unaltered or partly altered, could be so finely comminuted as to be most difficult of identification in the faecal pellets. One interesting feature is the similarity in shape of the fusiform pellets figured by Takahashi and those mentioned by Hadding (1932, p. 95, figs. 53, 54) and of the lobate grains figured by Galliher and by Hadding. In the Cambrian of the Montana-Wyoming area and the Mississippi Valley there is ample evidence of the availability of biotite and the abundance of faecal castings in the sediments. Both outcrops and cores show that the lands of Laurentia and Siouxia were composed of granitic and metamorphic rocks from which biotite could have been derived. Allen (1937) made a study of the Pre-Cambrian granites of Missouri and found them poor in biotite, a fact which he considered an absolute refutation of Galliher's evidence so far as the origin of glauconite in the Bonneterre dolomite was concerned. However, it should be noted that lithofacies maps indicate that after the deposition of the basal transgressive sandstone of the eastern shore and islands of Siouxia the supply of clastics gave out; and finer sand and silt grades (and possibly biotite) were drifted into this lime depositing region from the shores of Laurentia.

Depth of water. The water depth does not seem to be a critical factor in the formation of glauconite. Galliher has observed its formation in depths from 30 feet (5 fathoms) to 360 feet (60 fathoms); in Monterey Bay, depths of 330-342 feet (55-57 fathoms) are apparently the most favorable. Takahashi has observed glauconitization at depths of 21 feet in Mangaku-Uva, up to 60 feet (20 m.) in Setouchi and from 6-174 feet (1-29 fathoms) in Aomori Bay. Kuenen reports the presence of glauconite in bottom sediments from depths of 60 to 4450 meters with the greatest abundance between 250-750 meters, though in these samples it is not known how much of the glauconite is autochthonous. In the case of glauconite in the geologic record this same uncertainty exists, but it seems obvious, considering the prevalence and abundance of glauconite in the Cambrian from Montana and Wyoming to Wisconsin and south to Texas, that within this shelf area there must have been a number of sites of autochthonous glauconite.

Temperature of water. Glauconitization can occur within an appreciable temperature range. This is an especially important factor since recently (Cloud and Barnes, 1946) the presence of glauconite has been accepted as evidence of cool deep waters. Galliher reports that the water of Monterey Bay lies in nearly static layers with a temperature of about 4°C in the deepest parts of the channels (several hundred fathoms deeper than the favorable site of glauconitization) to 15°C near the surface. Takahashi finds that in stations around the Japanese Islands, the summer temperature of the surface waters must not be lower than 15°C, and at several stations 20°C or slightly more is recorded. Winter temperatures from 8°-10°C have been observed in favorable sites. The temperature control seems impressive in the Japanese Islands since Takahashi found glauconitization in progress much farther north on the west, Japan Sea side which has a branch of the warm current, Kuro-Siwo, than on the east side where the northeast coast is influenced by the cold current, Oya-Siwo. Recorded water temperatures in favorable stations range from 8°C to somewhat over 20°C, with the average around 14°-15°C, a temperate to warm temperate condition.

Turbulence of water. Both in recent sediments and in the geologic column, glauconite may be associated with evidences of agitated water--an apparent anomaly until it is realized that the phenomena of water motion indicates a sporadic or occasional violent wave or current action alternating with periods of quiet water. At Setouchi, Takahashi records the existence of strong tidal currents. In Monterey Bay, the water lies in nearly static layers, but the sediment in which the glauconite is now forming contains "a coarse fraction with all the characteristics of material deposited in well agitated water". (Galliher, 1935b, p. 1598) Galliher concludes that these deposits are a product of interstitial sedimentation, representing an earlier period of agitated water when the coarse fraction was deposited, and the present period of quiet water during which the fine silt and biotite settled between the coarser grains. Hadding noted a similar alteration of conditions in the Cambrian of Sweden, and in the Cambrian of the Montana-Wyoming area pebble conglomerates, and coarse ripple marked surfaces are intercalated with fine silts and beds of silty sand which have been thoroughly churned by mud-eaters.

Conditions of sedimentation. All sources agree that the formation of glauconite is definitely associated with a period of very slow or negative sedimentation on the sea floor. This is one of the few essential factors. In their samples Murray and Renard could demonstrate that glauconite was found only in the vicinity of continents built of solid crystalline rocks and where the coast was free of large rivers. Kuenen found exactly the same set of conditions existing in his samples from the Dutch East Indies. Galliher has emphasized the importance of the same correlation in the study of the Monterey Bay glauconite. Takahashi apparently did not consider these factors in his region. In the geologic column, as demonstrated by Hadding, the formation of glauconite is almost certainly associated with a marked decrease in sedimentation (especially of fine detritus) and a general failure of all types of sedimentation in a given area for a length of time. Similarly in the Montana-Wyoming Cambrian rocks, evidence of the existence of all these features at the time of their deposition has been offered.

Environment of sedimentation. Galliher and Takahashi by direct observation and Hadding by reasoning all conclude that a moderately anaerobic environment is essential for glauconitization. The rocks show pyrite and siderite associated with the glauconite, and the recent sediments give off a strong odor of H_2S when dredged. All three authors also note that an essential element of the environment is the presence of a large amount of putrefying organic material. Hadding emphasized this relationship in the Swedish sediments, and paleontologists have noted the abundance of fossils in all glauconite-bearing strata. As a consequence many have viewed this abundance as refuting the evidence from direct observation; but Hadding noted especially that only certain types of fossils are common in glauconite strata--trilobites, pelecypoda, gastropoda, brachiopoda, foraminifera; while other types--bryozoa, corals, stromatoporoids, sessile benthos requiring highly oxygenated water, are always absent. Actually, when the conditions are fully examined, there seems to be no serious discrepancy between the recent sediments and the fossil. Thus Galliher reports that glauconite is forming in quiet black muds and sands in an anaerobic environment, but notes that "oxidation may occur, of course, at the surface of the sediments. Organisms, principally worms, are apparently continually stirring the sediments ..." (Galliher, 1935b, p. 1590). This statement would indicate that conditions were suitable for certain forms of vagrant benthos. Galliher's map (1935b, fig. 1) is also important since it indicates the immediate juxtaposition of well-oxygenated neritic and sublittoral zones and the area of glauconitization. He has found glauconite forming on bottom stations from almost on shore (St. 115) to a distance of 5-10 miles from shore, and it is obvious that transfer of glauconite from one environment to the other needs only a period of strong wave or current action. In Mangaku-Uva, Takahashi finds small amounts of glauconite forming in a slightly anaerobic environment which becomes pronounced in summer when the organic content of the bottom becomes high. He described this station as a shallow saline lagoon with a bluish-black arenaceous mud bottom with numerous shells of larval Mollusca, Ostracoda, Foraminifera and echinoids. It is used as an oyster yard and seasonally is crowded by mud-eaters, eels and water plants. It seems quite probable that the mud-eaters of the Cambrian, worms, trilobites, and other unknown soft-bodied animals, were already adapted to such a moderately anaerobic bottom as those on which the living mud-eaters have been observed.

Furthermore on the extensive Cambrian shelf there would have been ample opportunity for local swales to develop anaerobic conditions in the hollows while surrounding, slightly higher, areas could support a bottom fauna with a higher oxygen need. The faunas of the two environments may be mixed after death, or as the trilobites molted. Only a few areas, the sites of the meadows of calcareous algae, and the Eoorthis and Billingsella beds, can now be positively identified as sites of highly oxygenated water at the time the deposits were being formed. The presence of a moderately anaerobic environment in which glauconite must form is not incompatible with evidence of an abundant bottom fauna of certain types of vagrant benthos.

The presence of glauconite in relative abundance in fossil sediments can be interpreted as indicating one or more sites of autochthonous glauconite within the area of deposition. The essential conditions of these sites are: 1) the presence of saline, probably marine, waters, 2) a very slow rate of sedimentation, 3) a moderately anaerobic environment in the bottom sediments, 4) a large amount of putrefying organic material available.

Concerning the sediments as a whole, the presence of glauconite strongly suggests that (1) the sediments were derived from land areas where crystalline rocks carrying biotite were exposed, and no large rivers reached the shore; (2) the sea bottom supported a large and varied fauna, with a biota of only scavengers and mud-eaters at the sites of glauconitization; (3) an appreciable amount of the glauconite in sediments is allochthonous.

The presence of glauconite in itself does not indicate any definite water temperature or water depth.

PROBABLE ECOGRAPHY OF THE MONTANA-WYOMING CAMBRIAN SEAS

All Cambrian deposition in the Montana-Wyoming area occurred, with one possible exception, in marine waters. Several authors have postulated that the non-fossiliferous condition of the Flathead sandstone indicates deposition in fresh or brackish waters prior to the transgressing sea. I believe it more probable that all the Flathead is a product of the transgressing seas. At the Pre-Cambrian contact clean-swept surfaces are more common than old soil profiles, though both are present. The basal beds are generally arkosic indicating brief reworking of the shore material before burial by the better sorted beach sands. A non-fossiliferous condition is normal for a littoral habitat for several reasons. The bodies of the living and the dead in this zone are in large part consumed by other animals, and the hard parts are subjected to the maximum effects of physical wear and leaching. In the Upper Cambrian we know that some snails had become adapted to a sublittoral if not a littoral environment; but so far as we know, the other members of these shore assemblages must have been soft-bodied animals, of whom we could hardly expect a trace in the sands. Since the littoral zone is an environment from which we rarely obtain a number of fossils in much younger sediments, the absence of fossils in the Cambrian littoral sands can not be regarded as very significant.

During the cycle of sedimentation under consideration (Middle Cambrian through Lower Ordovician) the shore occupied essentially one position during Middle Cambrian time and a second position during Upper Cambrian and Lower Ordovician time. Between the Dresbachian and Franconian and again between the Trempealeauian and Beekmantown there were two periods of shore instability. At the beginning of the Middle Cambrian the entire shelf or coastal plain of Laurentia and Siouxia was out of water and the shore lay in Utah and Idaho. During Albertella zone time the coast retreated eastward forming a slight embayment in central Wyoming. (Pl. 3). Although the details are not available, I believe that this coast was moderately irregular and fringed by a number of offshore islands. This position was maintained until early in the Upper Cambrian when the sea advanced rapidly eastward into the interior of the continent and the coastline of Laurentia lay almost entirely in Canada while Siouxia became either a large island or a northern peninsula of Llanoria. The position and the character of the Upper Cambrian shores are difficult to reconstruct because of later extensive erosion; but recent subsurface work suggests that the southern shore of Laurentia and the eastern and northeastern shores of Siouxia were embayed coasts with numerous granitic and quartzitic islands lying 100 miles or more offshore. The initial bold topography of the Upper Cambrian was apparently worn down during this time, for in Trempealeauian and Beekmantown time less and less clastic material is available for deposition. By this time also the slight downwarping of the area had carried most of the remaining islands below the sea.

Toward the end of Dresbachian time there is striking evidence in both Texas and the Upper Mississippi Valley of increased marine clastic deposition at first, later changing to the Welge and the Galesville non-marine sands. All over the shelf area to western Wyoming a sudden change can be observed to coarser clastics and locally, as at Sheep Mountain, disconformities exist. I believe that during this time the shores of Laurentia and Siouxia expanded greatly in the interior of the continent, and the disconformity at Sheep Mountain suggests that this movement may have extended all the way to the westward edge of the shelf area. In the regions involved there is a recognizable faunal break between the Aphelaspis and the Elvinia faunas, but since we are not familiar with the details of these faunas in the geosynclinal areas farther removed from the central land mass, it is difficult to evaluate the significance of the changing trilobite genera. After this disturbance the southern shore of Laurentia may have assumed very nearly its Dresbachian position; but subsurface and outcrop information indicates that the eastern and southeastern shores of Siouxia occupied different positions; i.e., parts of Kansas, Nebraska and Missouri remained exposed while areas in the Arbuckles were inundated for the first time.

The entire Montana-Wyoming area may be classified as a stable shelf, and, as such, in Upper Cambrian time was simply the western portion of a continuous shelf area extending to the Upper Mississippi Valley. Movement of the shelf was always slow, and in the form of broad regional downwarpings probably accompanied by slow regional upwarpings in the land sites of Laurentia and Siouxia. In the Middle Cambrian the amount of negative movement was greatest in northwestern Montana, presumably on the edge of the miogeosyncline, and decreased regularly to the east and southeast. Thus in

approximately the same time unit, 1,876 feet of sediment, 1,261 feet of it limestone, can be measured in the Kid Mountain section as against 500 feet, practically all clastics, in the Little Rocky Mountains, and 850 feet, half clastic and half limestone, in western Wyoming. In the Upper Cambrian the amount of negative movement over the shelf area from the Upper Mississippi Valley, to south central Montana and western Wyoming was remarkably uniform. Sediments averaging 500-600 feet, largely clastic, accumulated over this entire area; and only in the southwestern Montana sections, such as those in the Philipsburg district, does there occur evidence of rapid downwarping during the Upper Cambrian. Here the section is approximately 1,100 feet thick, including 800 feet of limestone.

In the early part of the Middle Cambrian, during deposition of the Flathead, the surface of the sea floor had a moderate relief judging by the marked variations observed in the thickness and character of the basal beds. Much of this relief was reduced by wave action and by fill of the basal sands, and presumably the initial irregularities were largely obliterated during the succeeding period of shale deposition. During the rest of Cambrian time there existed in the soft sediments of the sea floor several types of irregularities of shifting location but constant occurrence. Tidal and current scour produced dendritic and linear channels of varying depths (50 to several hundred feet or more) below the general surface of the shelf floor. Localized wave action and the slow or negative character of the sedimentation permitted certain areas to be built up while others lagged behind, thus producing swales where the bottom was appreciably lower than the surrounding areas. In western Wyoming and adjoining portions of Montana extensive shoal areas either just awash by the waves or only 20-30 feet below the surface must have existed for an appreciable length of time to permit the growth of the Tetonophycus and the Collenia magna algal meadows.

The character of the Cambrian sea bottom was quite variable during most of the time. The coarse littoral sands of the Flathead afforded a hard bottom temporarily. As deposition continued and land derived materials gradually failed, silt mixed with the sand even in the littoral areas to form soft bottoms. Over the rest of the area either mud or lime ooze accumulated. Only in the western portion of the region when the various algal meadows developed, is there good evidence of an extensive hard bottom. However, the flat pebbles would have afforded a hard bottom of a sort wherever they came to rest and remained unburied by silt for a time. Such pebbles formed a favorable site for crinoid beds during Trempealeauian time in south central Montana. The soft bottoms were favored sites of many types of mud-eaters, including many of the trilobites. The small inarticulate brachiopods must have found sufficiently firm areas of attachment on the surface of trilobite molts, other organic debris, and pebbles, but there is evidence that the larger articulates, Billingsella and Eoorthis, needed more extensive hard bottom for optimum development. These brachiopod beds occur in the region of the underlying Collenia magna meadows, and then not again as beds until the hard sand bottoms of the Upper Mississippi Valley are reached. A preference for hard bottom is shown by the shelled gastropods also, with the result that they are very poorly represented in Montana and Wyoming Cambrian faunas.

The seas over the Montana-Wyoming shelf were shallow during the entire Cambrian. The water depth was nowhere over 600 feet (100 fathoms) and this depth was attained possibly only in northwestern Montana. Over this region as well as the rest of the shelf it is believed that the average depth was considerably less. With the basal sandstone, a littoral environment passed eastward over the shelf but gave way relatively soon to a neritic environment with water depths of 100-200 feet. Some of the Middle Cambrian limestones appear to be Sloss's normal marine type, and may have been deposited in depths of 300 feet or so, but they also contain oolites and beds of fossils (presumably fragmental limestone) which indicate lesser depths, possibly 100 feet. The Middle Cambrian limestones also contain the small well-rounded pebble conglomerates which can be deposited farthest from shore and in the deepest water. But during the rest of the Cambrian, it is difficult to postulate water depths greater than 100-150 feet over the entire shelf area. In southwestern Montana the abundance of both oolites and Aulophycus in the Hasmark demands a depth suitable for turbulent water and one not greater than 150 feet for the algae. All the early Upper Cambrian limestones require a similar shallow water depth, while the algal meadows mentioned on page 60 demonstrate that, periodically, in many of these same regions, the water must have been only 1-30 feet deep. The question of actual subaerial exposure of portions of the sea floor on Upper Cambrian tidal flats is raised by the presence of the edgewise pebble conglomerates in which the lithology of the pebbles exhibits the same facies as the enclosing beds. While it has been noted that such conglomerates may be deposited in depths of 75 feet (Bucher, 1938) and possibly greater, the break-up into fragments is known only on tidal flats. We must assume that within the Montana-Wyoming shelf proper, local bottom areas were built up well above the profile of equilibrium and became shoals which were exposed sporadically at low tide. That these areas were more common in the direction of the shore line is shown by the increase in edgewise pebble conglomerates in the eastern sections; but that we cannot rely solely upon tidal flats along the shores is shown by the fact that the pebbles are a silty limestone and not a sandstone. For most of the Upper Cambrian the water depth may have averaged between 50-60 feet, with depths of only a few feet on the shoals, 100-150 feet in the local depressions and 200 feet or more in the main current channels, which presumably lay near the western edge of the shelf.

One of the most outstanding features of the Cambrian sediments is the contradictory evidence of the presence of both quiet static layers of water and marked turbulence of the waters. While the existence of such conditions may be assumed, it is difficult to reconstruct them into a satisfactory physical picture because the necessary information on geographic and atmospheric conditions at that time is lacking. I have assumed that under normal atmospheric conditions areas of quiet water would develop in the broad local swales on the sea floor, in shallow protected bays and lagoons, and along some of the deeper channels, thus affording sites for glauconitization. In these areas a mildly anaerobic environment would exist in the bottom sediments, either seasonally or for longer periods of time. The surface waters of these regions, like the rest of the shelf area, would be well oxygenated. The bottom waters over the rest of the shelf area would also be well oxygenated since these shallower portions of the sea floor would come well within the reach of waves. All shoals would experience the effect of

breakers and be sites of maximum oxygenation of the water. At long intervals violent storms (possibly of hurricane origin) would strike locally, providing wave and tide action strong enough to disturb the bottom sediments in quiet waters, and effect a mixing of the glauconite with organic debris and fragments from the flats and thus give rise to the pebble conglomerates: or sand and silt thus introduced into the quiet waters may settle and cover the glauconite deposit. The scattered glauconite grains in the Dresbachian limestones strongly suggest that they were carried into the clearer waters of the western areas by currents from the eastern shores.

Turbidity of the Cambrian seas must have varied much both in time and space. A specific regional pattern may be recognized upon which the local pattern of seasonal storms, tides and changing sea floor topography was superimposed. In the Middle Cambrian the shoreward zones of the sand and silt facies must have experienced more or less constantly turbid waters, with the opacity becoming more pronounced toward the northeast. Toward the west, and particularly to the southwest the water cleared, so that not infrequently calcareous algae produced limited biostromes. In the Upper Cambrian, marked and persistent opacity probably prevailed only in northeast Montana and adjoining Canada, and along the shores of local islands. Most of the area enjoyed periods of quiet clear water interrupted by local storms when the waves stirred up and shifted the fine silt and sands on the shallow bottoms. Even in the western half of the shelf area local turbidity of the water effectively halted algal development after the Elvinia zone. The slight increase in lime content in the Trempealeauian beds was probably due to the gradual failure of clastic materials rather than to any change in water conditions.

Although seriously handicapped by complete lack of knowledge of the geography of the western shore of the Cordilleran eugeosyncline, I have made an attempt to indicate some of the prevailing current directions in this area. (Pls. 7, 8). There was a boreal current moving southward in the Cordilleran eugeosyncline. Presumably in Canada it would have followed the western shore, and as it moved southward into the United States it veered slightly toward the east under the influence of the Westerlies and the cool water moved up over the shelf floor. However, I believe that the distribution of the early Upper Cambrian trilobite, Arapahoia, indicates that the main boreal current continued southward through the miogeosyncline. Over the shallow shelf area the cool bottom waters would move steadily east and southeastward into the interior of the continent while the warm surface waters would drift northward and westward. I believe this water movement was an important factor in the relatively rapid spread of the Upper Cambrian faunas into the interior and their cosmopolitan distribution during the Upper Cambrian. The planktonic protaspis, for example, could travel appreciable distances before taking up a benthonic life on a new sea bottom.

The absence of any animals closely related to modern faunas makes it difficult to judge the temperature of the water and the air. There is no evidence of any primary dolomites in the Cambrian sediments. The best clue to temperature seems to be the relatively large numbers of genera (and species, with modifications) which occur in a faunal assemblage. With the exception of the Aphelaspis zone fauna, the assemblages are most similar in

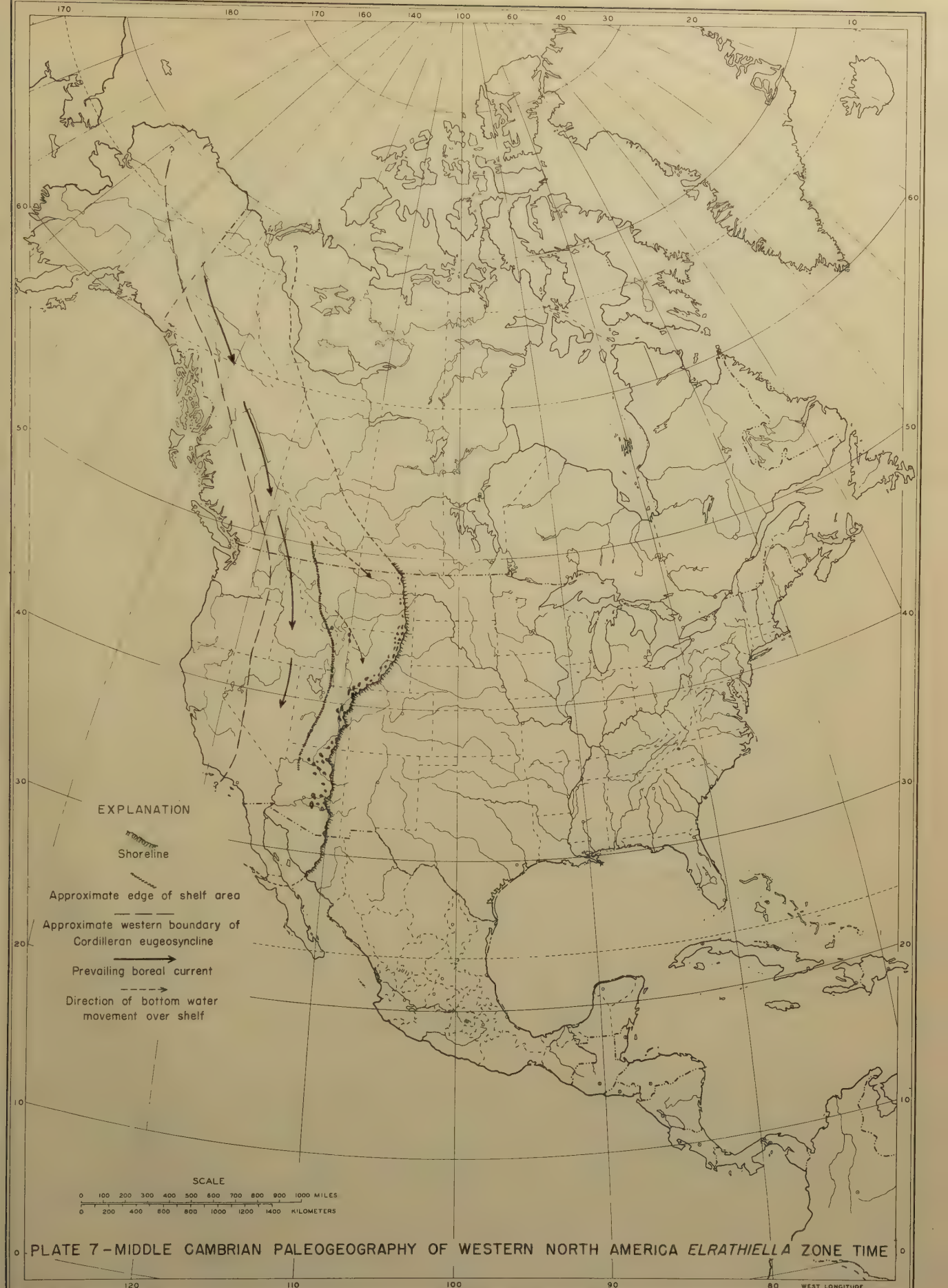

EXPLANATION
Shoreline
Approximate edge of shelf area
Approximate western boundary of Cordilleran eugeosyncline
Prevailing boreal current
Direction of bottom water movement over shelf
SCALE
0 100 200 300 400 500 600 700 800 900 1000 MILES
0 200 400 600 800 1000 1200 1400 KILOMETERS
170 180 170 160 140 100 60 40 30 20 10
120 110 100 90 80 WEST LONGITUDE
60 50 40 30 20 10 0

PLATE 7 – MIDDLE CAMBRIAN PALEOGEOGRAPHY OF WESTERN NORTH AMERICA *ELRATHIELLA* ZONE TIME

Goode base map - Copyright 1937 by the University of Chicago

size and variety to modern faunas of warm temperate seas. Possibly Takahashi's observation of a necessary summer temperature of not lower than 15°C for the formation of glauconite may be considered as significant here since it accords with the general faunal evidence. The limited number of genera (5) and wherever it occurs, large numbers of individuals of the Aphelaspis zone fauna, suggest a temporary change during this time to cooler water temperatures. Toward the end of the Upper Cambrian and during the early Ordovician a gradual rise in temperature may have taken place bringing even semi-tropical conditions into Montana and Wyoming.

The time span of approximately 92,000,000 years (Middle and Upper Cambrian and Lower Ordovician) gave ample opportunity for significant faunal variation to occur in these sediments. Though not spectacular because of the limited number of shelled animals preserved as fossils, these faunas record a large part of the development of the trilobites and the early evolution of the brachiopods. Eight or nine faunal zones are present, in the latest of which the trilobites are fewer in number and more specialized. No significant local faunal variation exists as all the zones are recognized elsewhere in the United States as well. Certain interesting horizontal faunal variations, such as the restricted occurrence of the brachiopod beds and the calcareous algae have been mentioned.

The most comparable region of recent sedimentation is the Baltic sea basin. The movement in the area is a slow up and downwarping of a portion of the continent producing a shallow stable shelf such as that postulated for the Montana-Wyoming Cambrian seas. Along the shores of the Baltic sea tidal flats with their trails, etc., the formation and the deposition of pebble conglomerates, and the deposits of sand and fine silt have been both observed and studied (Bucher, 1938). A moderately anaerobic environment has been recorded for portions of the bottom of the Baltic sea. The seaway is largely surrounded by land and contains a large number of off-shore islands similar to those in the Cambrian seas. Only in two respects does it differ: the Cambrian seas were of normal marine salinity; and the water and immediately surrounding shores enjoyed a higher temperature-- a warm temperate climate--than does the present Baltic sea, a feature probably attributable entirely to their different latitudes. Although the Montana-Wyoming area may be referred to as an inundated shelf of Laurentia and Siouxia, conditions in this area were not and should not be considered comparable to conditions in a region like the Atlantic coastal plain and continental shelf which is completely and directly exposed to the ocean.

SIGNIFICANT ORDOVICIAN EVENTS

A normal marine environment existed over the entire Montana-Wyoming shelf area during all the Upper Cambrian and at least the early part of the Lower Ordovician. Toward the end of the Trempealeauian, the southern shore of Laurentia was partially emergent, the coast line probably situated somewhere in the Dakotas. Thus the Montana-Wyoming area lay near the shore for a time, but throughout this entire region and the Black Hills of South Dakota, the same conditions of sedimentation continued without interruption.

This conclusion differs radically from that presented by Deiss (1936) and Lochman and Duncan (1944), when it was postulated that the Dry Creek shales represented the deposits of a supersaline regressive sea pushed eastward over Montana during Upper Cambrian time by the expanding shoreline of Montania. The crux of the paleogeographic interpretation has always rested upon the age and significance of the unfossiliferous red mudstones or ferruginous dolomites which Weed called the Dry Creek shale. Sloss and Laird (1947) have conclusively demonstrated that these unfossiliferous mudstones and dolomites belong to the Devonian cycle of sedimentation. The critical sections occur in the Little Rocky Mountains where these beds rest not upon Upper Cambrian as they do elsewhere in central Montana, but upon the Ordovician Bighorn dolomite. The differing ages of the top of the Cambrian sections in Montana and Wyoming is attributed to differential uplift and erosion during, a post-Beekmantown - pre-Bighorn period and again, during a longer post-Ordovician - pre-Devonian period. Montania, either as an island or a peninsula, and a supersaline regressive Cambrian sea, were both misinterpretations of post-Cambrian tectonic events.

A gradual slight upwarping cleared the marine waters from this shelf area in the later Lower Ordovician. Two positive centers controlled this movement. The major positive area, with a nearly symmetrical oval shape, centered in the eastern Big Belt Mountains. The amount of movement seems to have decreased proportionately away from this area in all directions. The symmetry of the pattern was destroyed and the western part of the dome concealed by the northeastward movement on a series of thrusts (probably during the Laramide Revolution) of the Helena and Philipsburg sections. This more recently developed asymmetry has added greatly to the difficulty of correct interpretation of the sections. To the southward movement also decreased regularly to the Montana line but in northwestern Wyoming, it was interrupted by another small oval area of positive movement, which, surprisingly enough, corresponds rather closely in position with the area of persistent shoals and/or islands recorded by the Cambrian sedimentation. Some effect of this positive element was already in evidence on the Upper Cambrian sea floor; but the interpretation of Horberg, Nelson and Church (1949) of this region as a depositional foreland with a depositional basin to the east in the Thermopolis-Wind River Canyon region is not correct, for the Cambrian and Lower Ordovician cycle of sedimentation at least. Their conclusions have been based upon the present observed thicknesses of the sections from west to east across Wyoming. A gross comparison of thicknesses does not give an accurate picture. In the Upper Cambrian under nearly comparable sedimentary conditions 180 feet of beds were deposited throughout the entire area, but in western Wyoming only those first 180 feet, up through the Conaspis zone, are now preserved, whereas in the east they are overlain by approximately 250 feet of younger Cambrian beds. In the Middle Cambrian part of the section both older beds and greater thicknesses of limestone demonstrate that the western sections lay farther from shore and on a more negative sea floor than the eastern sections. For the Cambrian sections of Wyoming, the differences in the observed sections must be attributed entirely to a post-Beekmantown upwarping of northwestern Wyoming and the resultant deeper erosion of this region. The area of minimum upwarping at this time, coinciding with the known occurrences of Beekmantown beds, shows a northwest trend from the northern Black Hills to the Big Snowy Mountains.

NORTH AMERICA

EXPLANATION
Shoreline
Approximate edge of shelf area
Approximate western boundary of Cordilleran eugeosyncline
Prevailing boreal current
Direction of bottom water movement over shelf
SCALE
0 100 200 300 400 500 600 700 800 900 1000 MILES
0 200 400 600 800 1000 1200 1400 KILOMETERS
170 180 170 160 140 100 60 40 30 20 10
120 110 100 90 80 WEST LONGITUDE
60 50 40 30 20 10 0

PLATE 8.-GENERALIZED UPPER CAMBRIAN PALEOGEOGRAPHY OF WESTERN NORTH AMERICA

Goode base map-Copyright 1937 by the University of Chicago

The buff, orange and red discoloration which regardless of their age characterizes the beds at the top of this sedimentary sequence must be attributed to subaerial erosion. Lochman and Duncan (1944) favored interpreting these beds as a zone of transitional sedimentation because of the gradual and sporadic appearance of the reddish coloration in clay stringers and the limy pebbles. This interpretation must be abandoned, and the Pilgrim-transition zone of central Montana, and the characteristic orange-buff coloring of the Grove Creek formation of southern Montana, must be recognized as the depth to which oxidation had penetrated in the limes and shales. Over the entire area the thickness of this discolored zone averages 35-40 feet. In the sections where it is overlain by the Bighorn dolomite, buff and orange are dominant and red uncommon, but where the Devonian overlies the Cambrian, as in central Montana, a deep maroon red prevails. Both contacts appear entirely conformable in the individual sections and some reworking and deposition of the clay soil occurred. This is especially conspicuous in central Montana where the ferruginous dolomites overlie with completely gradational contacts either reddish-stained green shales or slightly dolomitized pebble conglomerates. The Devonian sea encroached upon a land of low relief covered by a deep red clay soil, a material which imparted opacity and a high iron content to the water, features which, coupled with the clay bottom, would demand special adaptations by the marine faunas. These adaptations were apparently not made immediately because the beds remain wholly unfossiliferous as long as the red coloration is present.

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PALEOECOLOGY OF JURASSIC SEAS IN THE WESTERN INTERIOR OF THE UNITED STATES[9]

by

Ralph W. Imlay[10]

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ABSTRACT

Jurassic seas spread southward from the Arctic region four times into the western interior of North America. During Lower Jurassic time a narrow, shallow arm of the sea extended southward as far as southeastern British Columbia. During the Middle and Upper Jurassic epochs three successive seas extended about 2,500 miles south of the Arctic region and attained a maximum width of at least 800 miles. Each invasion spread farther south and southeast than the preceding one, but none connected directly with the Mexican sea or with the sea in the Pacific coast area. The site of most continuous marine deposition and of thickest accumulation was near the western margin of the seaway. Extensive areas in the eastern and southern parts of the seaway received gypsiferous redbeds suggestive of brackish-water or lagoonal origin. The bordering landmasses were mostly low, furnished few coarse sediments, and probably had arid climates except in the area west of Montana.

The Middle Jurassic sea, as indicated by its faunal assemblages and lithologic characteristics, was very shallow, warm, clear, generally well aerated, and its bottom in many places supported benthonic organisms.

The lower Callovian sea was extremely shallow throughout its eastern part, as indicated by an abundance of Lingulas and Ostreas and the presence of sandstones interpreted as littoral deposits. Lingulas were less common in the central and western parts of the sea, but an abundance of Gryphaea and other benthonic mollusks attests to the shallowness of the water. The fauna is similar to that of the Middle Jurassic except for the absence of corals and nerineid gastropods, which may indicate cooler waters during Callovian time.

The Oxfordian sea was probably somewhat deeper than the Callovian sea and locally the waters may have been stagnant, as indicated by pyritized fossils. However, some of the sandy beds along its western margin were probably deposited in the littoral zone, as indicated by the presence of Ostrea and Mytilus. Its deposits are distinguished from the underlying Jurassic rocks by having abundant glauconite and numerous belemnites. These probably signify an abundance of organic matter and of minerals, such as phosphate, derived from the lands to the west. The presence of considerable driftwood in the Oxfordian sandstone in Montana shows that the bordering lands were covered with vegetation. The faunal assemblage is similar to that of the lower Callovian, although most of the species are different.

INTRODUCTION

Understanding the relationships of the western interior Jurassic faunas to their environments involves first the assembling of lithologic, stratigraphic, and biologic data in an orderly manner and then the analyzing of those data to determine the source, composition, and means of deposition of the sediments, the depth and temperature of the sea water, the physical features and climate of the bordering landmasses, the character of the sea bottom, the habitats of the various organisms, and the changes in all these things during Jurassic time. The problem is difficult because there is no comparable broad, shallow sea today extending far into a continent and nearly surrounded by low borderlands. Furthermore, there are many areas for which the basic data have not been gathered. It is evident, also, that sound interpretations of all the data would require a greater scientific knowledge than now possessed by any one geologist. Still, a beginning in reconstructing paleoecologies should be made. Enough facts are available for all the geologic systems, or for parts of systems, to justify ecologic syntheses. These in turn will indicate areas where knowledge is lacking, will suggest worth-while research projects, and will stimulate specialists to formulate new explanations. Studies emphasizing the relationships of faunas and sediments are much more worth while to geologists than any amount of painful memorizing of index fossils, as the information gained can be interwoven with other scientific approaches, can be applied toward solution of field problems regardless of whether the organisms are known by name, and will furnish many useful clues of which some geologists might otherwise be blissfully unaware.

ACKNOWLEDGMENTS

This paper is based on the thousands of observations concerning the Jurassic of the western interior made by numerous field geologists, and it attempts to summarize the ecological aspects of their work. In a sense, all these geologists are collaborators in the present paper. However, the writer takes responsibility for matters of interpretation and speculation.

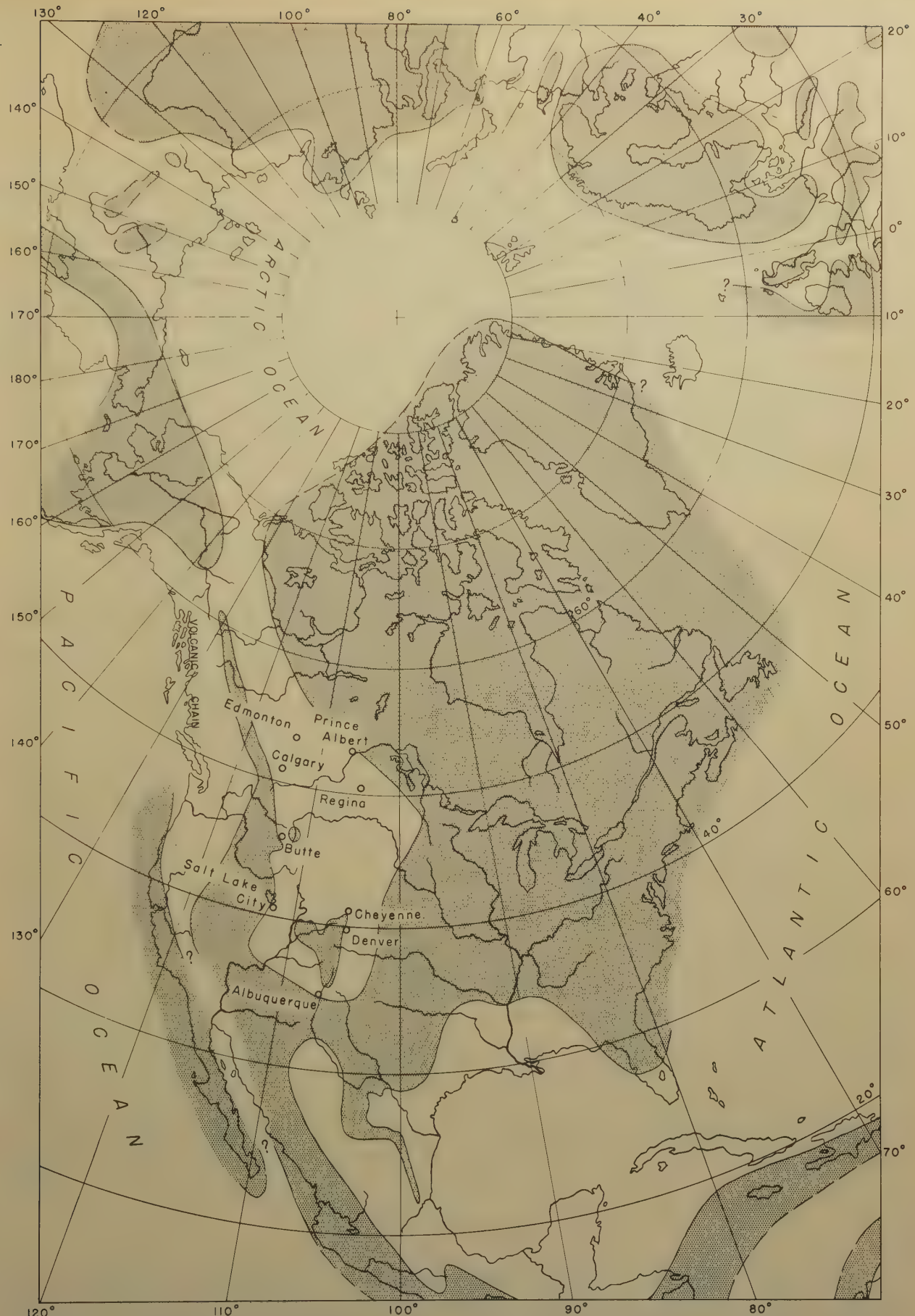


FIGURE 1. OXFORDIAN PALEOGEOGRAPHY OF THE BOREAL REGION. MODIFIED AFTER ARKELL, BUBNOFF, BURCKHARDT, CRICKMAY, FREBOLD, GRABAU, IMLAY, KOCH, KROPOTKIN, OBRUTSCHEV, SCHOTT, SCHATALOV, SCHUCHERT, AND UHLIG.

BORDERLANDS, ISLANDS, AND BASINS

The Jurassic sea of the western interior (fig. 1) was bounded on the west by a long, narrow landmass (Mesocordilleran geanticline) that extended from Mexico through the western United States into Canada as far as Yukon and was probably less than 200 miles wide in places. The sea was bounded on the south by a narrow landmass in southern New Mexico. It was separated from the Gulf sea to the southeast by uplifts in central Arkansas, southern Oklahoma, and central Texas -- a barrier that was probably never less than 270 miles wide even during the great extension of marine waters in Oxfordian time. It was bounded on the east in the area of Minnesota and eastern South Dakota by a southwestern extension of the Canadian shield. All the borderlands other than the Canadian shield must have been covered mainly with Triassic and Paleozoic rocks, as there are few places where the Jurassic rests directly on pre-Cambrian rocks. The borderlands were very low until near the end of the period, with the exception of an area in eastern Nevada during Lower Jurassic time.

The Jurassic seaway was divided into several subsidiary basins by broad, gentle uplifts in north-central Montana (Belt Island uplift) and west-central Colorado (Uncompahgre uplift) that gave rise to islands and extensive shallowly submerged areas (figs. 2-6). Between the uplift in Montana and the Canadian shield in Minnesota lay the northwest-trending Williston Basin of eastern Montana, western North Dakota, and southern Saskatchewan in which thicknesses of Jurassic rocks ranging from 800 to more than 1,100 feet have been penetrated by drilling. South of the Belt Island uplift in Montana and northern Wyoming was a broad eastward-trending basin that received sediment as great as 800 feet in thickness. The site of greatest sedimentation was along the western margin of the seaway in western Montana, eastern Idaho, westernmost Wyoming, and central Utah, as shown by at least 10,000 feet of sediment along the western margin of the Wasatch Plateau (Spieker, 1946, p. 125) in Utah and about 7,500 feet in southeastern Idaho. This thick mass of sediments thins rapidly eastward and changes markedly in facies within a distance of 30 miles or less (figs. 7 and 8). In Montana the change occurs along the line of the Sweetgrass arch and its southern continuation in the Big Belt-Bridger uplift. In western Wyoming the Darby-Absaroka lines of overthrusting coincide with changes in many formations, including those in the Jurassic system (Horberg et al., 1949, pp. 192, 204). In east-central Utah the Jurassic formations change considerably across the width of the San Rafael Swell. Similar changes occur in the Uinta Mountains of northeastern Utah (Thomas and Kruger, 1946, pp. 1277-1279) and in south-central Utah (Baker, Dane, and Reeside, 1936, pp. 6-8, 54, 55). These lithologic changes appear, therefore, to be related to structures that are aligned roughly parallel to the present western margin of Jurassic rocks, which is probably nearly parallel to the western borderland of the Jurassic seaway.

MARINE INVASIONS

During the Jurassic period marine waters spread southward from the Arctic region four times into the western interior of North America. These times were during the Lower Jurassic, the Middle Jurassic, and twice during

the Upper Jurassic (lower Callovian and lower Oxfordian) epochs. Each invasion spread somewhat farther south than the preceding one (Figs. 2-5), but none connected with the Mexican sea or with the seas on the Pacific coast, except remotely through the Yukon Territory or Alaska, although the intervening barriers must have been less than 200 miles wide in places. The seas in general were shallow, probably less than 300 feet in depth, and in central Montana and west-central Colorado were studded with islands and shallowly submerged areas. The site of most continuous marine deposition and probably of deepest water was near the western margin of the seaway. The Middle and Upper Jurassic seas were about 300 to 400 miles wide in the Arctic region of Canada, at least 800 miles wide in the latitude of Montana and North Dakota, and about 2,500 miles long. It seems probable that the lobate shape of these seas and the presence of islands and shallow submarine swells greatly hindered tidal and other currents and impeded renewal of water from the Arctic region, resulting thereby in warmer waters than in the Arctic region, the more rapid accumulation of fine-grained sediments in local basins, and a tendency toward saturation with calcium carbonate.

The Lower Jurassic sea in the western interior region of North America occupied a narrow trough extending southward along the present British Columbia-Alberta boundary toward Fernie in extreme southeastern British Columbia. It probably extended into northwestern Montana, but its deposits have not been identified there.

Early in the Middle Jurassic epoch, marine waters spread southward as far as northern Arizona and eastward across North Dakota but apparently barely reached western Colorado and did not cover southeastern Wyoming (fig. 3). Brackish-water and lagoonal conditions probably were widespread, as suggested by an extensive sequence of interbedded gypsum, dolomite, limestone, and redbeds. At the end of the epoch the sea withdrew from marginal areas, and disconformities were developed locally.

The lower Callovian sea covered nearly the same area as the Middle Jurassic sea but extended a little farther southeast in Wyoming and South Dakota (fig. 4). At the end of lower Callovian time an uplift in central Montana cut off the supply of normal marine[11] waters from the Arctic and produced continental conditions throughout a large area to the south, which continued to sink. A dead sea existed on the western side of the former seaway in Utah, southeastern Idaho, and southwestern Wyoming, where a considerable thickness of dark-red siltstone and silty sandstone containing bedded salt was deposited. Similar earthy[12] redbeds of slight thickness likewise were formed at the same general time in an area extending from southeastern Saskatchewan southward through the Dakotas into southeastern and south-central Wyoming (fig. 5). These beds appear to have been water-laid and may have been partly marine. Deposition appears to have been continuous, or nearly continuous, from Callovian into Oxfordian time except over an extensive area of uplift in Montana and northern Wyoming.

11/ Normal marine refers to sea water of normal salinity as contrasted with brackish or lagoonal waters or dead seas.

12/ Earthy means that much clay and silt are present.

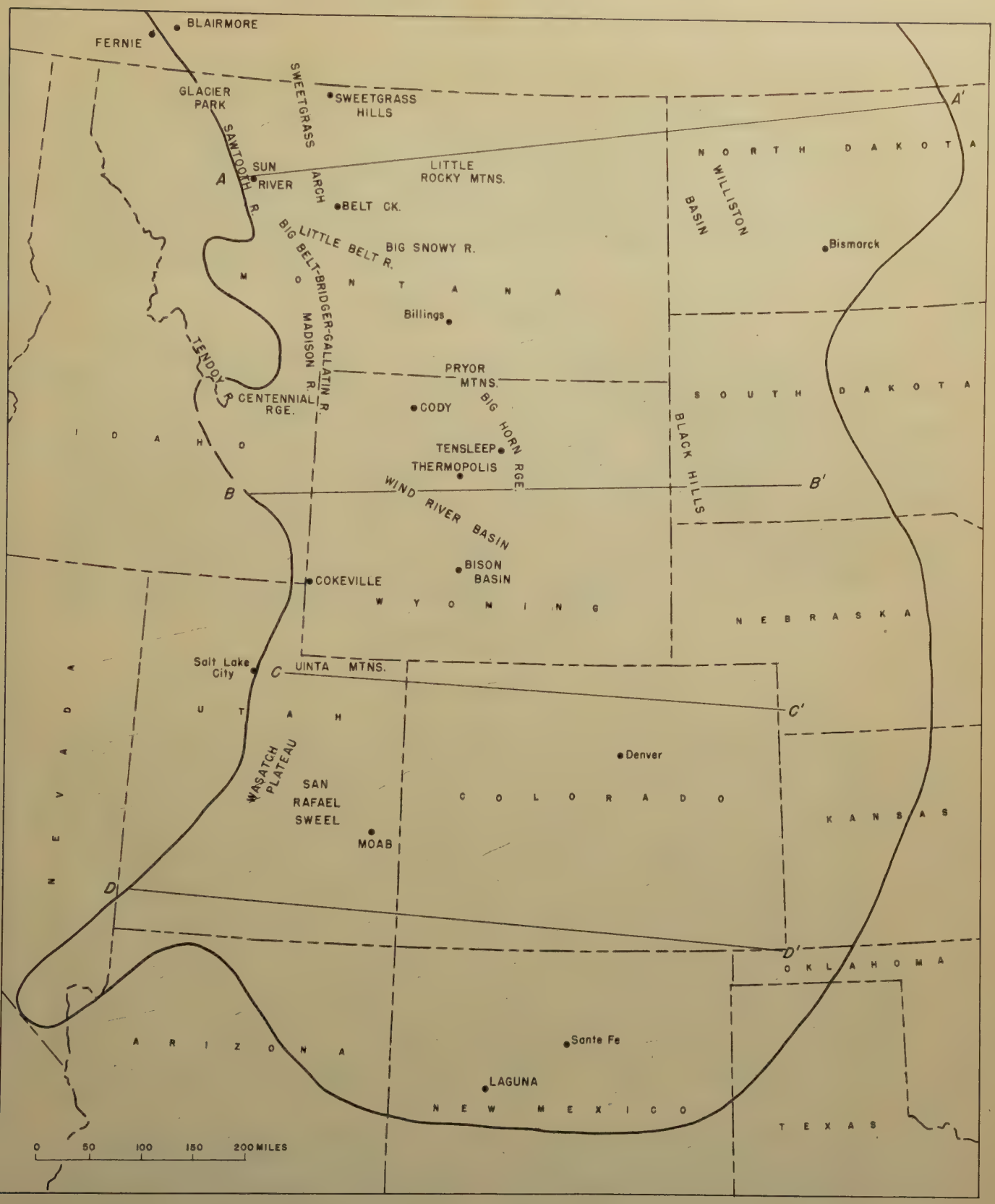


FIGURE 2. INDEX MAP OF THE WESTERN INTERIOR OF THE UNITED STATES SHOWING MARGIN OF JURASSIC DEPOSITS.

Early in the Oxfordian, marine waters spread rapidly southward and eastward beyond the limits of the older Jurassic beds (fig. 6). Normal marine deposits accumulated in areas that received limestone and shale during lower Callovian time, but brackish-water or lagoonal conditions existed in areas to the southeast and south, including southeastern Utah, northern Arizona, northern New Mexico, and southern and eastern Colorado. Near or at the end of the Oxfordian the sea withdrew into northern Alberta, and continental deposition was widespread over the western interior region during the remainder of the Jurassic.

SOURCES OF SEDIMENTS

The Jurassic seaway received clastic sediments from east, west, and south. During Lower Jurassic time most of the sediments appear to have come from the west. During Middle Jurassic time the lands east and southeast of the seaway probably contributed more sediment than the lands to the west. During lower Callovian time practically all the clastic sediment came from the east and southeast. During the middle and upper Callovian a source to the east and south is evident, but it seems probable that some sediment likewise came from the west. The Oxfordian sediments were derived almost entirely from the west except for a small area in northwestern Colorado. Evidence concerning the sources of sediments is presented under the heading "Conditions of deposition of constituent sediments".

SEDIMENTARY FACIES

Lower Jurassic

The rocks assigned to the Lower Jurassic in the western interior of North America comprise two facies that are entirely distinct and yet approach within 250 miles of each other. One of these is the lower member of the Fernie shale of British Columbia and Alberta and the other the Navajo and Nugget sandstones of the area south of Montana (table 1). The lower member of the Fernie shale near Fernie, British Columbia (Warren, 1934, pp. 59, 60), consists mainly of 50 to 150 feet of black shale but at its base includes 4 to 5 feet of phosphate rock. Deposition must have been extremely slow considering the time represented and the slight thickness of shale. Similarly, the presence of phosphate is supposed to indicate very slow deposition. The implications are that the lower member of the Fernie was deposited far distant from land or that the land was low and probably mantled with vegetation. Present knowledge of the distribution of the Jurassic in British Columbia, Alberta, and Montana indicates that the black shale of Lower Jurassic age was laid down in a narrow trough and that the second implication is the correct one.

These ideas regarding the bordering land areas and the rate of deposition are in marked contrast to those generally accepted for the origin of the Navajo and Nugget sandstones (fig. 3), which attain a thickness of at least 2,000 feet and are generally considered to be mainly of eolian origin (Baker, Dane, and Reeside, 1936, pp. 5, 6, 44, 51-53). This might be an argument against the Lower Jurassic age assignment of the Navajo and

Nugget sandstone. However, the characteristics of the upper part of the Lower Jurassic in southwestern Nevada (Muller and Ferguson, 1939, pp. 1616-1622) indicate that arid highlands did exist in Nevada. Therefore, the conclusion is drawn that the land barrier (Mesocordilleran geanticline) separating the western interior sea from the Pacific coast sea was high in the area of eastern Nevada and low in the area of eastern British Columbia, and that the climate changed similarly northward from arid to fairly humid.

Middle Jurassic

The Middle Jurassic is characterized over large areas in eastern Utah, central and northern Wyoming, and South Dakota by a gypsiferous redbed sequence that is generally less than 300 thick (figs. 3, 7, 8). These beds pass westward in Utah and Wyoming and northward in Montana and North Dakota into a sequence of limestone, dolomitic limestone, and gray shale that is as much as 800 feet thick in Idaho and 500 feet thick in Saskatchewan. However, gypsiferous redbeds are remarkably persistent at both the base and the top of the Middle Jurassic series throughout the southern part of the seaway as far north as southern Montana. North of the line of the Little Belt-Big Snowy Mountains in central Montana the upper redbeds are replaced by marine, yellowish, sandy to silty limestone, sandstone, and siltstone. West of the Sweetgrass arch in western Montana the entire Middle Jurassic consists of normal marine shale, limestone, and sandstone. The distribution of these facies was controlled by islands or shallowly submerged areas reflecting structural upwarps in west-central Montana, north-central Wyoming, and western Colorado that produced extensive lagoonal conditions in both early and late Middle Jurassic time and marginal lagoonal conditions throughout the subperiod. The character, thickness, distribution, and faunal content of the several facies show that the Middle Jurassic sea spread widely early in Bajocian time and deposited gypsum, redbeds, dolomite, and dolomitic limestone except in western Montana, where glauconitic sand and phosphatic shale were formed. The sea deepened during upper Bajocian and lower Bathonian time, extended farther southward and eastward, and deposited limestone, dolomitic limestone, and gray shale over the earlier-formed redbeds, although in marginal areas there was commingling of redbeds with dolomite and limestone. The sea retreated in the upper Bathonian, resulting again in deposition of redbeds, but the waters were probably not as shallow as during the lower Bajocian, because very little gypsum was formed and normal marine waters persisted in Idaho and in western and northern Montana.

Lower Callovian

Lower Callovian sediments are a little more widespread than Middle Jurassic sediments in the western interior and consist mostly of normal marine sandstone, shale, and limestone (figs. 4,7, 8). However, the southern end of the seaway contains some lagoonal or brackish-water sediments. In eastern Utah, northeastern Arizona, and northwestern New Mexico, 100 feet or less of soft red sandstone and sandy shale was deposited. These redbeds pass westward in southern and central Utah through a sequence of greenish-gray shale, yellow to greenish-gray sandstone, gypsum, and thin limestone beds into a much thicker sequence of gray shale and thin-bedded limestone. In northern Utah, as exposed along the Uinta Mountains, they

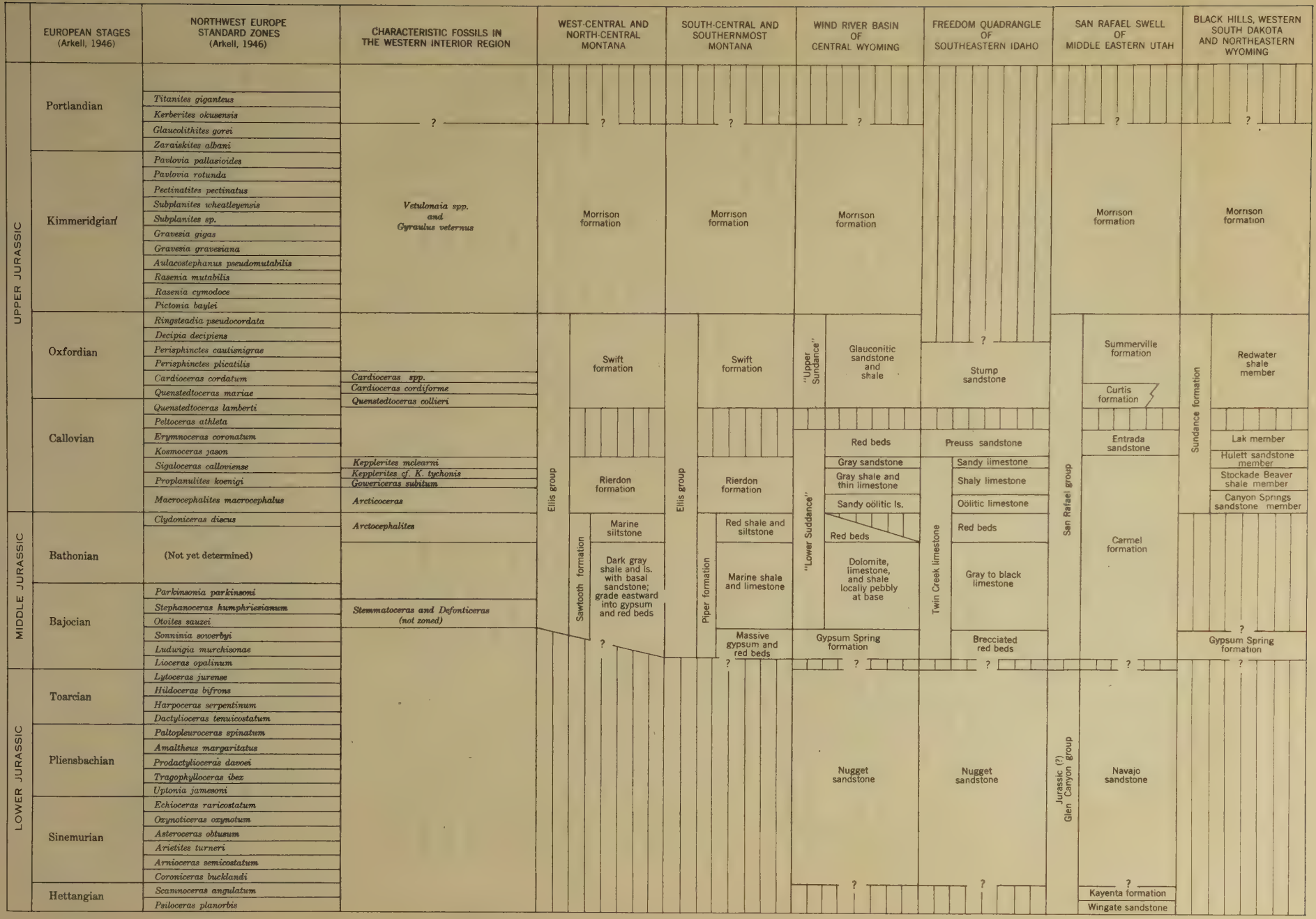


TABLE 1. CORRELATION OF THE JURASSIC FORMATIONS IN PARTS OF THE WESTERN INTERIOR REGION

pass westward into hundreds of feet of gray thin-bedded to shaly limestone and gray shale. Most of the change in Utah occurs in a distance of about 40 miles. Equivalent beds in the upper part of the Twin Creek limestone of southwestern Wyoming and southeastern Idaho consist mostly of thinbedded to shaly limestone but at their base include from 200 to 300 feet of hard, medium-bedded, partly oölitic limestone and at their top from 100 to 150 feet of silty to sandy limestone that passes westward into a glauconitic sandstone. These upper beds of the Twin Creek thicken westward from about 700 to 1,800 feet, but practically all the thickening occurs in their medial shaly limestone portion.

The lower Callovian beds of Wyoming, Montana, and the Dakotas consist dominantly of soft, calcareous gray shale that becomes sandier to the southeast and is interbedded with thin beds of limestone to the northwest (fig. 7). Sandstone members characterize both the base and the top of the sequence in central and eastern Wyoming and western South Dakota. The basal sandstone, called the Canyon Springs sandstone member of the Sundance formation, occurs sporadically, fills the irregularities of an erosion surface, and is medium-grained and partly oölitic. It greatly resembles the Nugget sandstone, from which it may have been derived. It grades westward along the western margin of the Big Horn Mountains into a sandy oölitic limestone that persists westward as an oölitic limestone into Idaho and southwestern Montana. The upper sandstone, called the Hulett sandstone member of the Sundance formation, is fine-grained, gray, calcareous, thin- to thick-bedded, and is characterized by oscillation ripple marks. It thickens eastward at the expense of the underlying Stockade Beaver shale member of the Sundance formation. It extends westward toward Cody in northwestern Wyoming and is present in southeastern Montana and most of North Dakota. In northwestern Wyoming and in southern Montana it passes into dark-gray shale, but in southwestern Wyoming a similar sand appears at the same stratigraphic position at the top of the Twin Creek limestone. In central Montana the Hulett sandstone member becomes oölitic and then passes into a chalky limestone that persists northward into Saskatchewan and marks the top of the Rierdon formation over a large area. The lower Callovian of Montana west of the wedge of the Hulett sandstone member consists mainly of calcareous gray shale and gray limestone. Limestone predominates in the Little Rock Mountains and in the subsurface in central Montana, but shale predominates in the Sweetgrass arch area.

Upper Callovian

Deposits of upper Callovian age in the western interior comprise two facies that occupy different areas and yet grade into each other within short distances (figs. 5, 7, 8). One consists mainly of dark-red earthy or silty sandstone that locally is salt-bearing and is even-bedded but not cross-bedded. The other is a light-colored sandstone characterized by clean, rounded quartz grains that are generally of two sizes, by conspicuous color banding of red, pink, gray, and white, and by large-scale cross-bedding. The larger grains are generally well rounded and frosted and are scattered through a matrix of much smaller and remarkably even-sized grains. This light-colored, cross-bedded facies is the Entrada sandstone of the

Colorado Plateau area. It is generally less than 400 feet thick but in south-central Utah exceeds 1,000 feet. It passes westward within about 30 miles in southwest Utah, in the San Rafael Swell of east-central Utah, and in the Uinta Mountains into a thicker, a dark-red, silty sandstone facies that is called Entrada sandstone in central and southwestern Utah and Preuss sandstone farther north. Likewise it is replaced northward along the southern margin of Wyoming by a red to yellow, earthy, even-bedded sandstone that passes northeastward in the Dakotas into a thin redbed unit called the Lak member of the Sundance formation. Bedded rock salt occurs only in the red earthy facies of north-central Utah, southwestern Wyoming, and southeastern Idaho (Mansfield, 1927, p. 340; Spieker, 1946, pp. 124, 125). The stratigraphic position of the salt in Idaho appears to be in the lower part of the Preuss sandstone. In Utah the salt occurs at a comparable stratigraphic position. Both sandstone facies are gradational downward into lower Callovian marine or brackish-water beds. Their upper contract is generally sharp and in the San Rafael Swell and the Uinta Mountains of Utah is disconformable. However, in New Mexico, Arizona, and southern Colorado the Entrada sandstone grades upward into gypsum and limestone belonging to the Todilto member of the Wanakah formation, which is correlated with the Curtis formation farther north.

Oxfordian

The Oxfordian sediments of the western interior are mostly normal marine (figs. 6-8). They are brackish-water and lagoonal in the same general area that is underlain by the light-colored, clean sandstone facies of the Entrada, which includes northern New Mexico, northern Arizona, southeastern Utah, and southwestern and eastern Colorado. The brackish-water and lagoonal sediments can be subdivided into two facies occupying fairly distinct areas, although merging laterally to some extent. Probably the most conspicuous of these facies is the Summerville formation (Gilluly and Reeside, 1928, p. 79; Baker, Dane, and Reeside, 1936, pp. 8, 9, 46), which extends from the San Rafael Swell of east-central Utah southeastward into southwestern Colorado and northeastern Arizona. On the San Rafael Swell the Summerville consists mainly of even-bedded, thin-bedded, red and white, fine-grained sandstone and maroon shale but includes some bedded gypsum and many chalcedony concretions. It changes eastward and southward into brownish-red sandstone and ripple-marked sandy shale, and siltstone that locally contains much chert. It is generally less than 400 feet thick and thins eastward and southward. The upper part of the Summerville extends farther northwest than the lower part. The Summerville grades laterally in southwestern Colorado, northern Arizona, and northwestern New Mexico into a thinner, more calcareous facies called the Wanakah formation. This is characterized at its base by the Todilto limestone member, which locally passes into thick masses of gypsum. East of Laguna, New Mexico, and in eastern Colorado gypsum is much more common than limestone at the base of the Wanakah formation. Its general absence west of Laguna may be related to pre-Morrison erosion. The upper part of the Wanakah formation consists mostly of sandstone, shale, and marl and greatly resembles the Summerville formation; but it is lighter in color, thicker bedded, more calcareous, and coarser grained. In eastern New Mexico this part may be represented by 30 to 70

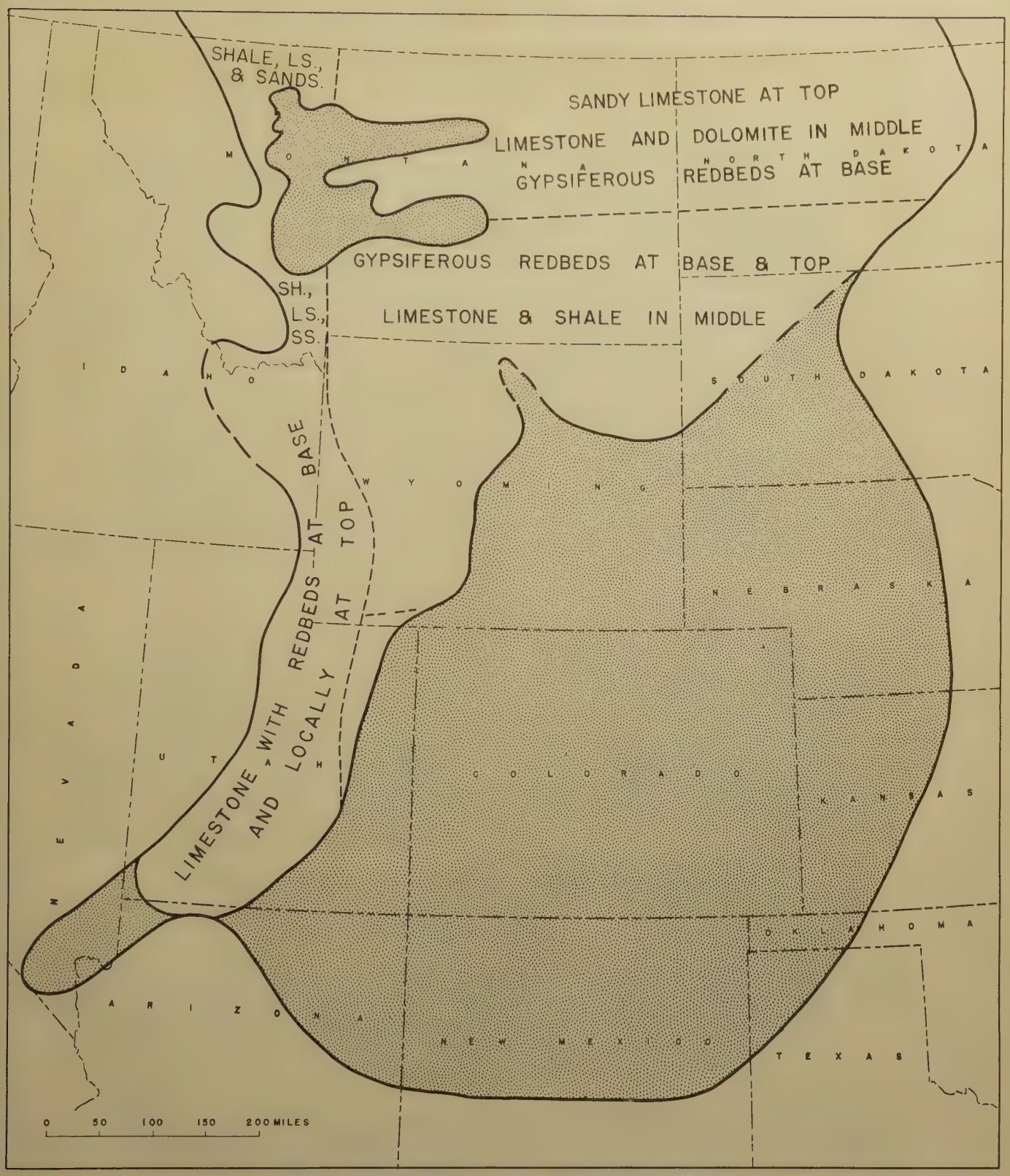


FIGURE 3. DISTRIBUTION OF MIDDLE JURASSIC DEPOSITS.

feet of sandy shale and sandstone bearing red and green chert concretions (Goldman and Spencer, 1941, pp. 1762-1764; Dobrovolny and Summerson, 1946) at present included in the Morrison formation.

The normal marine facies of the Oxfordian extends southward into northwestern Colorado and southwestern Utah. In Utah it consists mainly of fine-grained, glauconitic, greenish-gray, thin- to medium-bedded sandstone but contains some greenish-gray shale and gypsum and becomes finer-grained eastward and southward. North of Utah it comprises two laterally intergrading facies. On the west it consists dominantly of calcareous sandstone (Stump sandstone and Swift formation) and on the east dominantly of dark greenish-gray shale (Redwater shale member of the Sundance formation). Shaliness increases eastward from the base upward, resulting thereby in most sections having a lower shale member and an upper sandstone member. Sandy limestone beds are common, except in central and southern Utah. Glauconite is the most characteristic constituent of both the sandstone and shale facies and is generally abundant basally. This serves to distinguish the Oxfordian marine beds from underlying beds, in which glauconite is uncommon or absent. The contact with the overlying Morrison formation appears to be conformable in all parts of the western interior and to represent a gradual change from deposition of marine glauconitic sandstone, limestone, and shale to nonmarine varicolored silty shale, siltstone, sandstone, and gray silty limestone.

Kimmeridgian and Portlandian

There is no faunal evidence for the existence of marine waters in the western interior of the United States after Oxfordian time. If marine waters persisted anywhere, the most likely area was from eastern Wyoming northward into southeastern Saskatchewan, because that area subsided more during Oxfordian time than adjoining areas and may therefore have had slightly deeper water. Also, in eastern Wyoming some sandstone units near the top of the Sundance formation have considerable silty and clayey material, as do sandstones in the Morrison formation, which suggests that the sea may have retreated in an oscillatory manner.

CONDITIONS OF DEPOSITION OF CONSTITUENT SEDIMENTS

Conglomerate

Conglomeratic beds are uncommon in the marine Jurassic of the western interior. They have been found at the base of and within the Middle Jurassic, at the base of the Callovian, and the base of the Oxfordian.

Marine sandstone

Marine sandstone was uncommon during Middle Jurassic time but became nearly as widespread as marine shale during the Callovian and Oxfordian, although its total amount was always much less than that of shale. The Oxfordian is generally considered to be represented mainly by a sandstone facies, probably because the bulk of the shale facies is out of view in the subsurface of eastern Montana, eastern Wyoming, and the Dakotas.

Marine siltstone and shale

Marine siltstone and shale may be discussed together, because in many areas they are intimately associated and pass laterally into each other imperceptibly. Marine shale of Middle Jurassic age is common only in westernmost Montana and northwestern Wyoming. Marine shale of lower Callovian age is widespread in western Montana and Wyoming and passes eastward into interbedded shale and siltstone in eastern Wyoming and South and North Dakota. Oxfordian calcareous shale and siltstone of medium to dark greenish-gray color is well developed in the Black Hills area in South Dakota and in eastern Wyoming, where it is known as the Redwater shale member of the Sundance formation. This member at its top includes some sandstone and thin beds of oölitic to coquinoid limestone. Its base is generally marked by a unit of highly glauconitic sandstone. It extends northward through North Dakota and eastern Montana into southeastern Saskatchewan. It passes westward into a dominant sandstone sequence known as the Swift formation in Montana and the Stump sandstone in western Wyoming and Idaho. The most abundant fossils in the shale are belemnites, pectens, and Foraminifera, but locally some of the limestone or sandstone beds contain a great variety of pelecypods. Ammonites occur mostly in concretions. It seems likely that the Redwater shale member was deposited in somewhat deeper waters than the underlying Callovian shale and sandstone, because its sandstone beds are not ripple-marked and generally do not carry Gryphaea or Ostrea. Sources of clastic sediments were from the west, except possibly for the basal sands.

Limestone

Limestone is the most dominant rock in the Middle Jurassic of the western interior region, is fairly abundant in the lower Callovian, and is subordinate to shale and sandstone in the Oxfordian. It ranges from shaly to thick-bedded, it may be silty or sandy, and it grades laterally and vertically into shale, siltstone, and sandstone. Its color ranges from light gray to black, or locally yellowish or brownish. It is oölitic near the tops or bottoms of certain stratigraphic units. It is dolomitic only where associated with redbeds and gypsum.

All the Middle Jurassic limestone in the western interior appears to have been deposited in very shallow waters, as attested by an abundant molluscan fauna, frequent occurrence of Gryphaea and Ostrea, many oölitic beds, and lateral gradation into redbeds and gypsum along the eastern margin of the seaway. The presence of some corals and nerineid gastropods suggests that the waters were warm. The grayish-black limestone near the base of the Twin Creek limestone in southeastern Idaho and western Wyoming is correlated faunally with the grayish-black phosphatic shales in the Middle Jurassic of western Montana and probably reflects incomplete aeration of the sea bottom.

Lower Callovian limestone was formed only in the western part of the Jurassic seaway, and the main area of deposition was from southeastern Idaho southward. The limestone, representing the upper two thirds of the Twin Creek limestone, is characteristically shaly to thin-bedded, medium- to

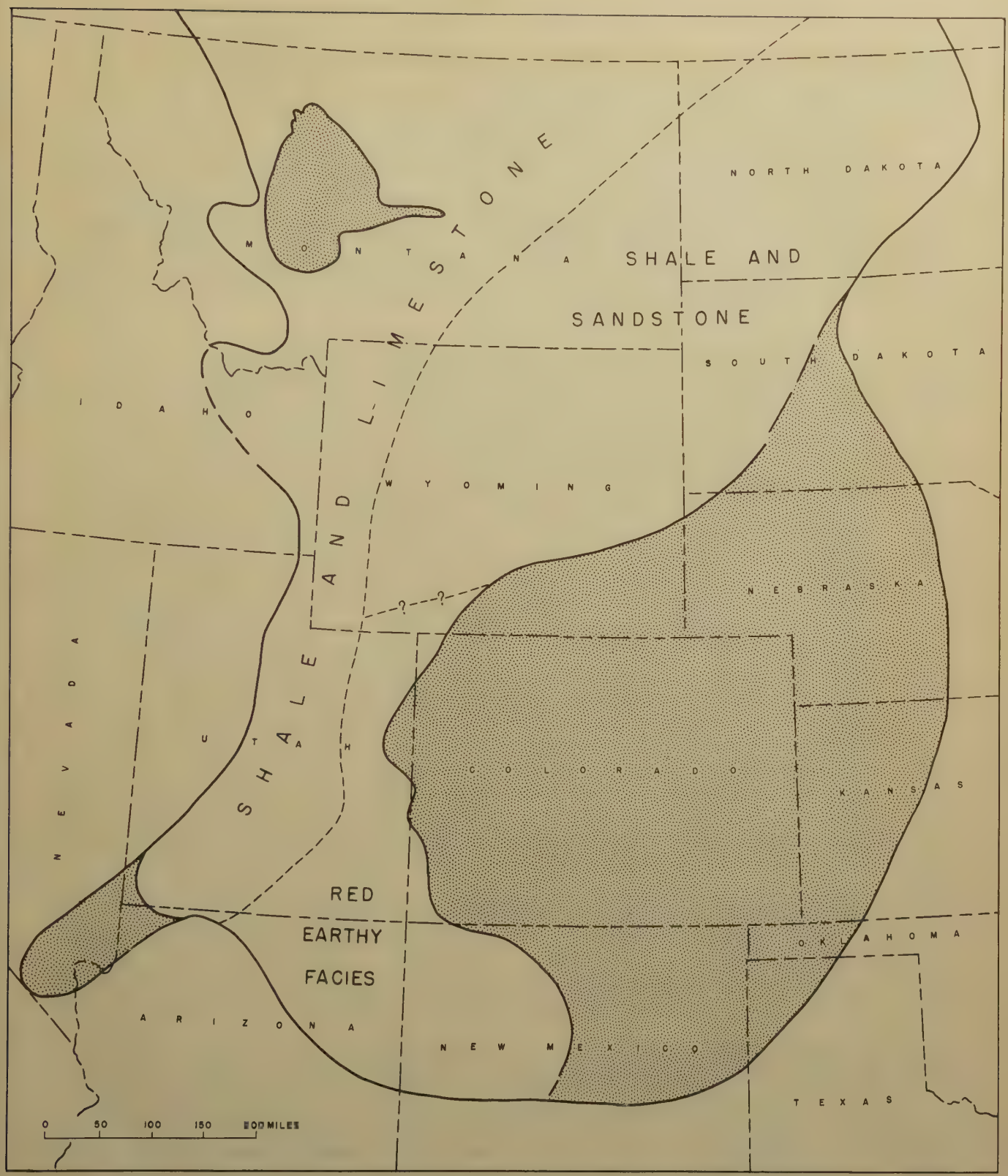


FIGURE 4. DISTRIBUTION OF LOWER CALLOVIAN DEPOSITS.

light-gray, dense or porcellaneous, and contains few fossils. In Idaho it attains a thickness of about 1,500 feet and basally is characterized by 200 to 300 feet of hard, medium-bedded, cliff-forming limestone, of which some beds are oölitic. It grades eastward rapidly into much thinner, highly fossiliferous gray shale and shaly limestone in Wyoming and into redbeds in Utah. The fossils found most frequently in the limestone facies consist of free-swimming or free-floating forms, such as belemnites, crinoids, and Camptonectes. Occasional layers have furnished a few bottom-dwelling pelecypods, such as Astarte, Tringonia, and Pinna, which occur in many kinds of sediment. Gryphaea has been found in the basal oölitic beds and along the eastern margin of the facies, where it is thinner and shalier than farther west.

A chemical origin for most of the upper part of the Twin Creek limestone is suggested by its fine texture, general lack of organic matter, and scarcity of fossils. Its thickness, considering the short time involved, indicates rapid subsidence. It probably was deposited in a deeper part of the neritic zone than most of the Jurassic sediments in the western interior, but the general absence of benthonic mollusks may be explained by local unfavorable bottom conditions, perhaps induced by rapid subsidence accompanied by equally rapid deposition of lime mud. The availability of calcium carbonate in the sea water is shown by the abundance of benthonic organisms in the lower Callovian shales and limestones of parts of Wyoming and Montana east and north of the area in which the Twin Creek limestone was deposited. If the sea water was saturated with calcium carbonate, then precipitation of that salt might keep pace with subsidence of the sea floor and in areas of rapid subsidence form a soft bottom on which benthonic organisms could not live. In areas of slow subsidence the slow deposition of lime mud locally permitted compaction sufficient for organisms to become attached. Also, the need of benthonic organisms for freely circulating waters is more apt to be met in areas of slow than of rapid deposition. If deposition kept pace with subsidence, then the Callovian part of the Twin Creek limestone was probably deposited entirely in very shallow water. This is shown by the oölitic beds at its base, the sandy, ripple-marked limestone at its top, and the occurrence locally of one to four redbed units in its upper part. In general, the westward change from highly fossiliferous beds in western Wyoming to dense limestone in Idaho resembles a similar change at about the 10-fathom line in the Straits of Florida (Thorp, 1939, p. 285), but the change in character of the deposits in Wyoming and Idaho reflects the differences in sedimentation between platform and geosynclinal areas, which does not appear to be the case in Florida.

Lower Callovian limestone in Montana and northwestern Wyoming, in most sections, consists of thin interbeds in a shale sequence. However, in the Little Rocky Mountains and in the subsurface of central Montana the lower Callovian is mostly shaly to thin-bedded limestone. The presence of limestone in this area probably reflects the distance from a source of clastic sediment to the southeast and the presence of Belt Island to the west, which formed a barrier and furnished very little sediment until Oxfordian time. The thin limestone beds generally contain a large molluscan fauna, including Gryphaea and Ostrea, that proves deposition in fairly shallow water.

Oxfordian limestone in the western interior region occurs in two distinct areas separated by an area of sandstone and shale in central Utah. The northern area includes all the seaway northward from northern Colorado and Utah. In it limestone occurs frequently as sandy, oölitic, or coquinoid beds, especially in the upper part of the Oxfordian sequence. The sandy limestones pass laterally and vertically into calcareous sandstones, and consequently the designation of certain beds as limestone or sandstone is somewhat arbitrary. A shallow-water origin for the limestone beds is shown by their intimate association with ripple-marked sandstone, by the presence of oölites, and by the occurrence in some beds of a varied pelecypod fauna, including Gryphaea and Ostrea.

The southern area of limestone deposition during Oxfordian time includes northeastern Arizona, northwestern New Mexico, and southwestern Colorado. The limestone, called the Todilto limestone member of the Wanakah formation is 30 feet or less in thickness, thin-bedded to shaly, bituminous to asphaltic, typically dense, but locally sandy, and grades downward into the Entrada sandstone. It is locally gypsiferous and east of Laguna, N. Mex., is replaced by a thicker gypsiferous facies. In places it is overlain directly by the Morrison formation and in others by an intervening sequence of shale and sandstone similar to the Summerville formation of southeastern Utah (Baker, Dane, and Reeside, 1936, pp. 9, 17; Baker, Dane, and Reeside, 1947, pp. 1664, 1668). The presence of these overlying beds suggests that it represents only the lower part of the Oxfordian. It has furnished fish of possible marine and brackish-water affinities (Dunkle, 1942; Koerner, 1930) on the Piedra River in southwestern Colorado and in northeastern New Mexico. It is considered to have been deposited under subnormal marine conditions at the southern margin of the sea and to have an origin similar to that of the associated gypsum, which will be discussed later.

Dolomite

The Jurassic system of the western interior contains dolomite only in the Gypsum Spring formation of northern Wyoming (Love et al., 1945) and in equivalent beds in Montana (Imlay et al., 1948), North and South Dakota (Imlay, 1947, pp. 236-244; Jones, 1940, p. 130), southeastern Saskatchewan, and southwestern Manitoba (Wickenden, 1932; 1934; 1945, pp. 8, 9, 65, 70, 71; Fraser et al., 1935, pp. 11-13). The dolomite generally is medium gray and ribboned but may be reddish or light gray. It grades laterally into limestone and gypsum and is interbedded with these, as well as with red sandstone, red and green siltstone, and shale. It is unfossiliferous in most places but locally contains a varied fauna of pelecypods, gastropods, and echinoids (Love et al., 1945). Deposition in very shallow marine waters is shown by the associated fossils and by gypsum beds.

Gypsum

Gypsum occurs as a widespread mass at the base of the Middle Jurassic and as thin beds and lenses higher in the Middle Jurassic throughout most of the western interior seaway (figs. 3, 7). Bedded gypsum of Callovian age is known only in Utah, Idaho, and extreme southwestern Wyoming. Bedded

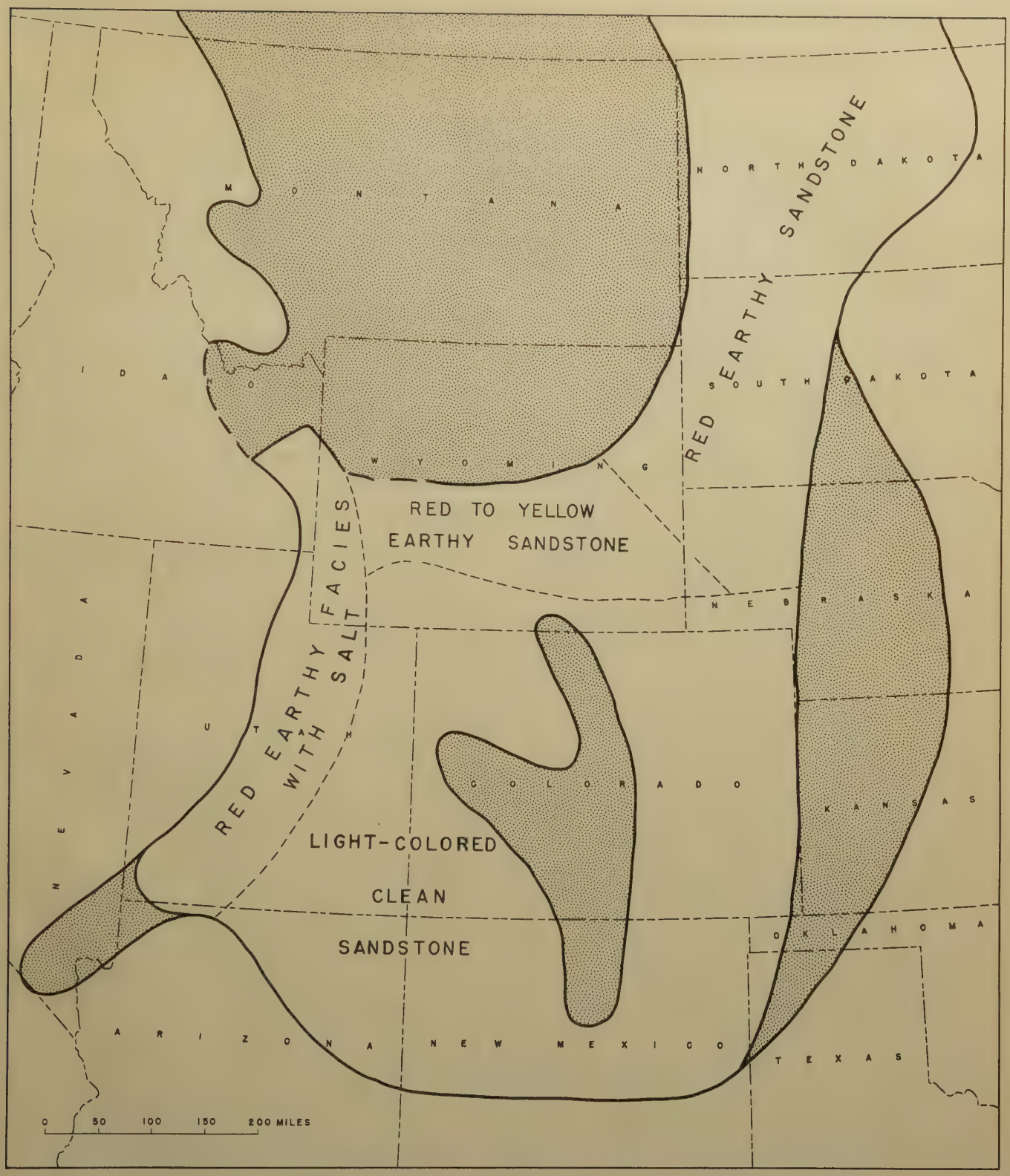


FIGURE 5. DISTRIBUTION OF UPPER CALLOVIAN DEPOSITS.

gypsum of Oxfordian age is widespread in Utah, Arizona, New Mexico, and southwestern and eastern Colorado. Selenite crystals occur frequently in dark marine shale of lower Callovian and Oxfordian ages in Wyoming and Montana.

The most persistent mass of gypsum is at or near the base of the Middle Jurassic throughout most of western and northern Wyoming, in Montana east of the line of the Sweetgrass arch and Big Belt Mountains, in North and South Dakota, and in southern Manitoba and Saskatchewan. The gypsum does not appear to be as persistent north of the line of the Big Snowy-Little Belt Mountains as farther south, but few records are available. It is generally missing in southeastern Idaho, the bordering part of Wyoming, and in north-central Utah, but its former existence there is suggested by the presence of a unit of brecciated limestone and red siltstone within the basal redbed member of the Twin Creek limestone. This brecciated unit, near the continental divide in northwestern Wyoming, passes eastward into a massive, white gypsum unit from 50 to 125 feet thick that characterizes the lower part of the Gypsum Spring formation of north-central Wyoming (Love et al., 1945). The change from brecciated beds to gypsum can be observed at the outcrop in a number of places. The gypsum is represented in the subsurface by white anhydrite. It is underlain by about 25 to 50 feet of red, slightly sandy siltstone and overlain by 50 to 150 feet or more of red shale and siltstone interbedded with some gypsum, dolomite, and thin beds of limestone. The dolomite and limestone locally contain marine pelecypods and gastropods of Middle Jurassic age. These gypsiferous redbeds are overlain in northwestern Wyoming and southern Montana by limestone and shale that contain ammonites of middle Bajocian age. Above these marine beds is a rather widespread redbed member that locally bears lenses of gypsum.

The widespread gypsum mass at the base of the Middle Jurassic probably represents the initial deposits of the Middle Jurassic marine transgression. It is conceivable that the gypsum accumulated slowly during a large part of the Lower Jurassic period, but its thickness is not so great as to require more than a small part of the Bajocian stage. Much thicker gypsum masses are known elsewhere that accumulated during a small part of a period (Imlay, 1940 a, pp. 35, 36; Kelly, 1936, pp. 1022-1029; Imlay, 1944, p. 1163). The large areal extent of the gypsum at the same stratigraphic position suggests that it was formed nearly simultaneously in a single body of water rather than in numerous lagoons, that the depth of water was exceedingly shallow and uniform throughout a large area, and that the climate was so arid that few streams entered the sea. Conditions leading to the precipitation of gypsum were undoubtedly favored by the presence in west-central Montana of a large island which with submarine extensions northward and eastward served as a partial barrier to normal marine waters. Precipitation of some thin lenses of gypsum persisted along the eastern margin of the seaway in north-central Wyoming and southernmost Montana all during Middle Jurassic time, indicating that an arid climate continued, that the waters remained very shallow, and that there were local barriers. Some of these barriers may have been structural, as minor northwest folding in the western part of the Wind River Basin during the Middle and Upper Jurassic epochs has been suggested by Love et al. (1945). North of the line of the Little Belt-Big Snowy Mountains the middle part of the Middle Jurassic is only slightly gypsiferous and the upper part contains no gypsum, which suggests fairly broad connections with the open sea in Canada.

The origin of the Oxfordian gypsum is related to a large island in west-central Colorado. This island had northeast and northwest prongs that greatly hindered free entry of marine waters from the north into the southern end of the seaway. The northwest prong furnished much more sand to the sea than any other part of the island. It seems significant that most of the area in which Oxfordian gypsum was deposited had received, during the upper Callovian, a mantle of clean, light-colored sandstone, which most geologists have interpreted as of eolian origin. This area of sand became flooded in early Oxfordian time by extremely shallow marine waters, giving rise to broad sea flats bordering the island and locally to lagoonal conditions. Gypsum and limestone probably were laid down in depressions between sand dunes and locally became interbedded with sand blown from the tops of the dunes or from the island. Deposition of gypsum and limestone was followed in many areas by a slight thickness of sand and clay that appear to be water-laid but are unfossiliferous. The northwest prong of the island continued to shed considerable sand, producing a tongue of sand (Moab tongue of Entrada sandstone) in the sea to the north and lagoonal conditions in the sea to the west.

Salt

Jurassic salt deposits in the western interior are known only in north-central Utah, southeastern Idaho, and adjoining parts of Wyoming. The salt in Idaho and Wyoming is in beds from 6 to 29 feet thick associated with plane-bedded red siltstone, red shale, and a little gypsum in the lower part of the Preuss sandstone (Mansfield, 1927, pp. 99, 338-340). Its age on the basis of stratigraphic position is upper Callovian. The salt in central Utah, west of the Wasatch Plateau, is associated with dark-red shale (Spieker, 1946, p. 124; Eardley, 1933, pp. 330-334), which is probably correlative with the basal part of the Preuss sandstone.

These occurrences of bedded salt show that a dead sea or large saline lake or series of saline lakes existed from central Utah northward into southeastern Idaho during the upper Callovian. Regional studies show that deposition of the salt and associated redbeds coincided with a broad uplift in central Montana, which effectively cut off the southern part of the seaway from direct access to marine waters to the north (Imlay, 1947, pp. 258, 259). It also coincided with the development in the Colorado Plateau area of clean, light-colored, coarsely cross-bedded sandstone that is generally considered to be continental and at least in part eolian. All this indicates great aridity and continental conditions in the western interior region during upper Callovian time.

Siliceous material

Siliceous material is uncommon in the Jurassic system and occurs mainly in Middle Jurassic limestone, dolomite, and red shale. Silicified fossils have been found in the lower part of the Twin Creek limestone in Idaho and western Wyoming. Silicified limestone occurs locally in the Carmel formation in Utah (Baker, Dane, and Reeside, 1936, p. 23). Siliceous cement has been noted in the Entrada sandstone. Some chert and small, rounded opalized masses occur

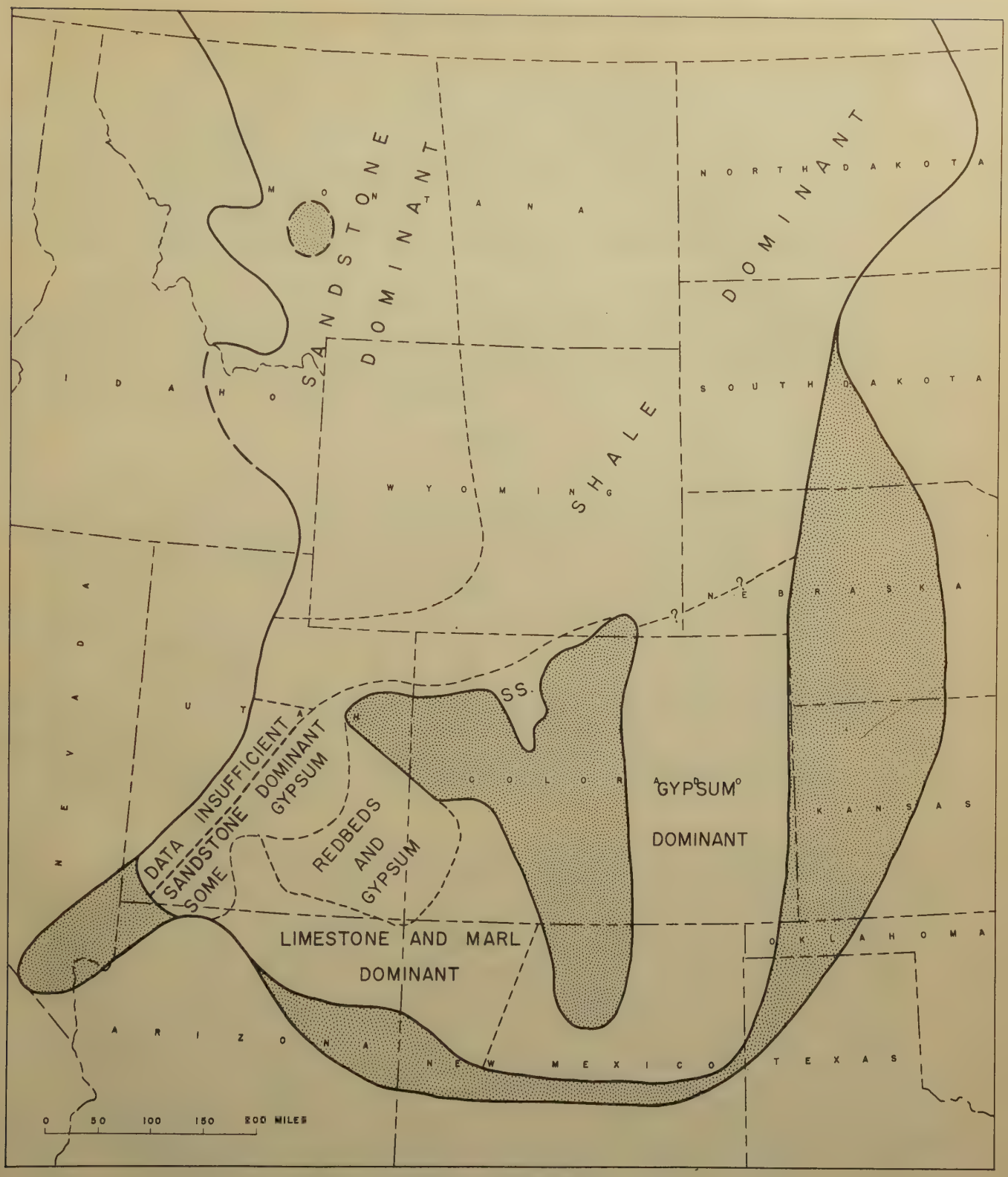


FIGURE 6. DISTRIBUTION OF OXFORDIAN DEPOSITS.

in the Middle Jurassic in north-central Wyoming, eastern Montana, the Dakotas, and Saskatchewan. The chert is dark gray or reddish gray and occurs as thin layers or small blocky irregular masses that grade laterally into dolomitic limestone or dolomite. Opalized masses ranging from 1 to 4 inches or more in diameter are fairly common in the Gypsum Spring formation of north-central Wyoming. They are most common in the upper part of the formation but in some sections, as near Tensleep, Wyo., occur at various levels and locally have been incorporated in a conglomerate at the base of the overlying Sundance formation. Similar opalized masses have been found in the Middle Jurassic subsurface beds of southeastern Saskatchewan.

The general absence of chert in the Callovian and Oxfordian sediments is not surprising, considering that they are mostly sandstone and shale. The scarcity of chert in the Middle Jurassic may mean that very little silica was being brought into the sea. This might happen under conditions of great aridity on bordering landmasses.

Redbeds

Redbeds are very common in the Jurassic system of the western interior region (figs. 7, 8). Most of the marine formations become reddish in marginal areas of deposition bordering landmasses. In addition, there are three extensive redbed units that cover a large part of the seaway and reflect important paleogeographic changes. One of these is at the base of the Middle Jurassic and marks the first invasion of marine waters in the Jurassic. Another is at the top of the Middle Jurassic and marks restriction and shallowing of marine waters. The other is in the upper Callovian and marks a time of uplift in Montana, which cut off the seaway to the south and led to the formation of saline lakes and deserts in that area. These widespread redbed units have generally received formational or member rank, but in areas of marginal deposits they may not seem to be of any greater significance than other redbed units that represent local reddening of normal marine beds.

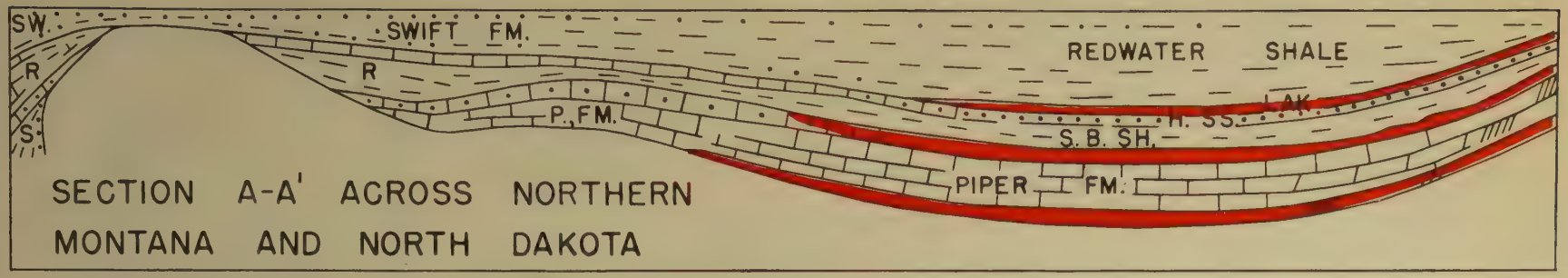
Red siltstone and shale at the base of the Middle Jurassic is widespread in southern Montana, northern and western Wyoming, and southeastern Idaho. Some red sandstone and shale at the base of the Carmel formation in central and southwestern Utah (Baker, Dane, and Reeside, 1936, p. 6) are probably of the same age. Basal Middle Jurassic redbeds in north-central Wyoming are included in the Gypsum Spring formation (Love, 1945); in Montana are in the lower member of the Piper formation (Imlay et al., 1948), and in southeastern Idaho and adjoining parts of Wyoming are in the basal member of the Twin Creek limestone. Redbeds at the same position occur in the Dakotas, Saskatchewan, and Manitoba. The redbeds are mostly a brownish red but some are light red, and some thin beds are green, greenish gray, or mottled purple and gray. They are locally slightly sandy, especially near the base, and may contain one or more beds of yellow to red sandstone. They are interbedded with thin beds and nodules of gray dolomite, white chalky dolomitic limestone, and many beds of white gypsum. One massive bed of gypsum, as much as 125 feet thick, occurs in the lower part of the redbeds over a large area in northern Wyoming and southern Montana and probably at one time existed in Idaho, western Wyoming, and north-central Utah. The total thickness of the redbeds and associated sediments ranges from about 75 to 250 feet.

These redbeds and associated gypsum and dolomite are the initial deposits of a sea that spread eastward and southward around a large island in the area of central Montana early in Middle Jurassic time. A peninsula, or island, apparently existed in the Big Horn Mountain area of north-central Wyoming. The islands and their submarine extensions divided the sea into a number of basins and lagoons and hindered movement of normal marine waters from the north. Bordering landmasses must have been very low, judging by the scarcity of sandy material and the general slight thickness of the deposits. Some of the red silt and clay may have been reworked from older redbeds of Triassic or Permian age to the south and southeast. Other sources were probably distant, because the presence of extensive masses of gypsum suggests a fairly hot and arid climate on the lands bordering the sea.

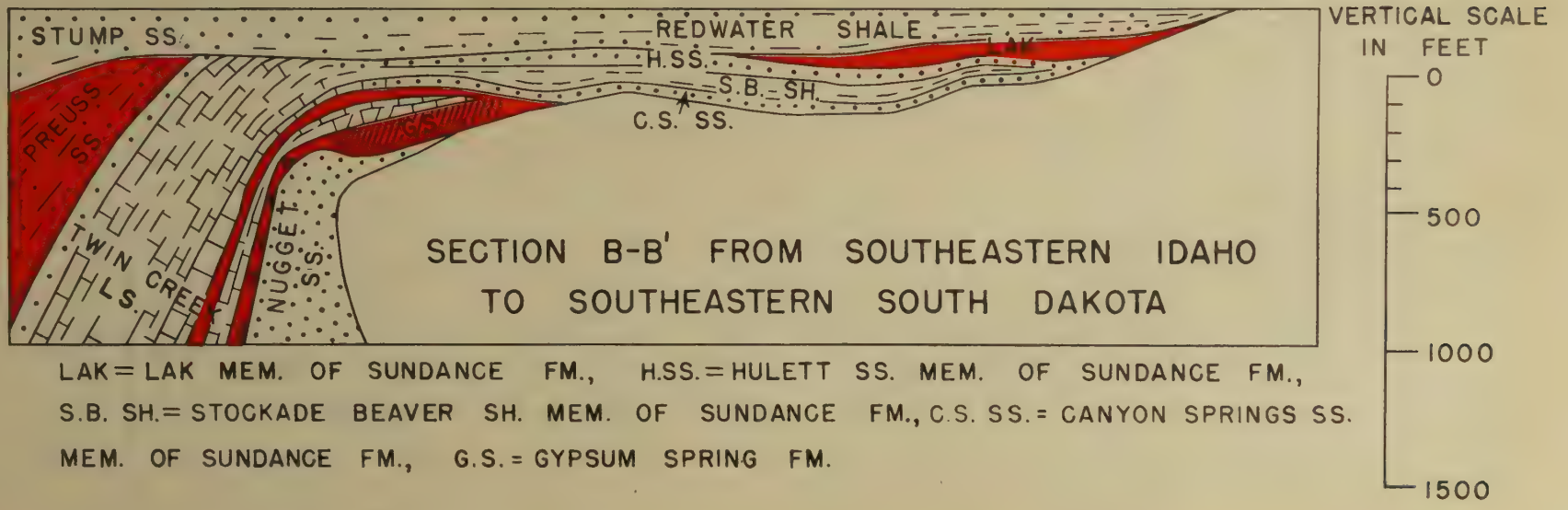
A unit of soft red sandstone, siltstone, and shale at the top of the Middle Jurassic has been recognized in southern Montana, south of the Big Snowy Mountains and east of the Madison Range (Imlay et al., 1948), and in northwestern Wyoming. It passes westward in Idaho and northward in Montana into yellowish silty to sandy limestone and calcareous siltstone containing marine fossils of late Middle Jurassic age. It is mostly dark red or brownish red, but some beds are pink, brown, purple, green, or gray. Locally it contains interbeds of oölitic gray limestone or white gypsum. Its thickness ranges from 20 to 130 feet. It differs from the redbed unit at the base of the Middle Jurassic by being thinner, more sandy and silty, and less gypsiferous.

This redbed unit represents a shallowing of the sea at the end of the Middle Jurassic epoch. Partial barriers were formed in central Montana along the line of the Little Belt-Big Snowy Mountains and in western Montana along the line of the Big Belt-Bridger-Gallatin Mountains. A minor uplift on Belt Island in central Montana and perhaps on the adjoining borderlands furnished some sand to the seas. The source of clay was probably to the southeast, as equivalent beds north of the Little Belt and Big Snowy Mountains consist mostly of marine siltstone or silty to sandy limestone. The scarcity of gypsum and the lateral gradation of redbeds into normal marine beds show that marine connections remained fairly open.

The extensive redbeds of the upper Callovian are represented by the thick Preuss sandstone of southeastern Idaho, southwestern Wyoming, and north-central Utah; the moderately thick red earthy facies of the Entrada sandstone of central and southwestern Utah; and the thin Lak member of the Sundance formation in central and eastern Wyoming, South Dakota, North Dakota, Saskatchewan, and probably southern Manitoba. These units are characterized by homogeneous, very fine grained sandstone and sandy siltstone that are dark red to maroon and plan-bedded. A few beds are greenish gray, pink, or rarely white. The sand grains are generally well rounded. Cross-bedding has never been noted, and oscillation ripple marks are uncommon. The bedding ranges from thin to massive and is generally poorly developed. These redbed units do not contain fossils but grade downward into marine beds of lower Callovian age. Their lower part in Idaho, and in central Utah, contains bedded rock salt. They grade laterally in the Colorado Plateau into clean, light-colored, cross-bedded sandstones that are generally interpreted as mostly wind-deposited. They are overlain sharply and locally disconformably by glauconitic marine sandstone and shale of lower Oxfordian age.



SW = SWIFT FM., R = RIERDON FM., S = SAWTOOTH FM., LAK = LAK MEMBER OF SUNDANCE FM., H.SS. = HULETT SS. MEM., S.B. SH. = STOCKADE BEAVER SH. MEM., P.FM. = PIPER FM.



LAK = LAK MEM. OF SUNDANCE FM., H.SS. = HULETT SS. MEM. OF SUNDANCE FM., S.B. SH. = STOCKADE BEAVER SH. MEM. OF SUNDANCE FM., C.S. SS. = CANYON SPRINGS SS. MEM. OF SUNDANCE FM., G.S. = GYPSUM SPRING FM.

FIGURE 7. DIAGRAMMATIC CROSS SECTIONS OF JURASSIC DEPOSITS IN NORTHERN PART OF WESTERN INTERIOR REGION

These redbed units are basally of marine or brackish-water origin, as they grade downward into marine beds. Their homogeneous character, even bedding and lack of cross-bedding, suggests deposition in fairly quiet waters. Their dark red color suggest deposition under oxidizing conditions, such as might be found in brackish or highly saline waters. The presence of bedded rock salt in the lower part of the Preuss sandstone shows that deposition there was in a dead sea or saline lake. The complete absence of fossils favors a highly saline rather than brackish-water environment. Lateral gradation in the Colorado Plateau into coarsely cross-bedded sandstone suggests that that area was a desert. All these factors indicate that the redbeds in question were laid down in one or more large bodies of highly saline waters and that the bordering lands were hot and arid.

Marginal redbed facies of considerable extent existed during lower Callovian and Oxfordian times in eastern Utah and adjoining parts of Colorado, New Mexico, and Arizona. This area was favorable for the deposition of redbeds, as it was at the southern end of the seaway and on the western margin of a small positive element that furnished some sand and clay during Callovian and Oxfordian time. Such an area would be covered by the shallowest part of the sea, would be inundated less often, or for shorter times, than the more open sea to the north and northwest, and would easily be divided into subsidiary basins by the usual processes of wave erosion and transportation of bottom sediments or by minor structural changes. The marginal redbed facies of lower Callovian age is known as the eastern part of the Carmel formation. It is generally less than 100 feet thick and thins eastward to a featheredge. It consists of pink, red, or reddish-brown sandy shales and red sandstones that are interbedded with considerable gypsum in the thicker western sections and are highly contorted at many places (Baker, Dane, and Reeside, 1936, pp. 6, 7). It has not furnished fossils but grades westward into gray, reddish, and greenish shales interbedded with much gypsum, which grades still farther westward into gray siltstone, shale, and limestone. It overlies the Navajo sandstone sharply and is overlain transitionally by the clean, light-colored, cross-bedded facies of the Entrada sandstone. The lower Callovian age of the thin eastern red sandy phase of the Carmel is based mainly on stratigraphic position and on the eastward wedging out of Middle Jurassic rocks between Whiterocks and Vernal in northeastern Utah.

The marginal redbed facies of Oxfordian age in east-central and southeastern Utah is known as the Summerville formation. It is generally less than 400 feet thick and thins out eastward and southward. On the San Rafael Swell it consists of even, thin-bedded red and white fine-grained sandstone interbedded with red siltstone and shale and some gypsum. Small pinkish chalcedony nodules and crusts are common. Mud cracks and ripple marks are abundant. The Summerville has not furnished fossils but grades westward in central Utah into the fossiliferous Curtis formation, its upper part extending farther west than its lower part (Baker, Dane, and Reeside, 1936, pp. 8, 9). Near Moab, in east-central Utah, it grades eastward into the Moab tongue of the Entrada sandstone, which is of lower Curtis age (Baker, Dobbin, McKnight, and Reeside, 1927, p. 804; McKnight, 1940, pp. 89, 97, 98).

Other marginal redbed units of smaller extent were formed during Jurassic time. In southeastern Idaho and westernmost Wyoming the upper part of the Twin Creek limestone contains locally from one to four thin redbed units. These are of lower Callovian age. In southeastern Wyoming pinkish beds occur locally in the lower part of the Sundance formation below the Lak member and in the upper part of the Sundance.

These marginal redbed units in the lower Callovian and the Oxfordian probably reflect both brackish-water and lagoonal conditions. Lagoonal conditions in eastern Utah are implied by the presence of bedded gypsum and are favored by the shallowness of the sea and a source of sand in west-central Colorado, resulting in sand tongues and probably offshore bars. The thin red units in the upper part of the Twin Creek limestone in Idaho and Wyoming seem to be anticipatory of the overlying red Preuss sandstone, suggesting that they were deposited in an abnormally saline rather than a brackish-water environment. Perhaps the general scarcity of fossils in the upper part of the Twin Creek limestone is due to abnormal salinity of the water in which it was deposited.

Glauconite

Glauconite in the western interior Jurassic is widespread and abundant only in the Oxfordian sandstones and shales. It has also been found near the base and top of the Middle Jurassic beds in southeastern Idaho and northwestern Montana and in lower Callovian beds in Idaho, eastern Wyoming, and western South Dakota. In the Oxfordian it is much more common in the basal sandstone than in higher beds. All the other occurrences mark the beginning or the end of marine deposition.

Glauconite in the lower Bajocian of southeastern Idaho is in sandstone beds in the lowest limestone member of the Twin Creek limestone. This limestone member was deposited in shallow water, as shown by the presence of numerous pelecypods and some gastropods. Glauconite in the lower Bajocian of northwestern Montana occurs in a basal ripple-marked sandstone and in sandy beds in the lower part of the middle shale member of the Sawtooth formation. The glauconitic sandstone beds are finely pyritic, greenish gray to dark green, and contain many phosphate nodules and water-worn fragments of belemnites. The associated shales are grayish black, fissile to chunky, and finely pyritic. Associated fossils include a variety of mollusks, including Ostrea and Trigonia. These glauconitic sandstones are the initial deposits of a transgressive sea. The ripple marks and water-worn belemnites show wave activity. The abundance of organic matter, pyrite, and phosphate suggests reducing conditions and probably slow deposition. The presence of Ostrea and Trigonia is proof that the waters were fairly shallow.

A small amount of glauconite occurs in the upper silty to sandy member of the Sawtooth formation in northern Montana (Cobban, 1945, p. 1273). This member contains many ammonites and pelecypods, including such shallow-water forms as Gryphaea and Ostrea.

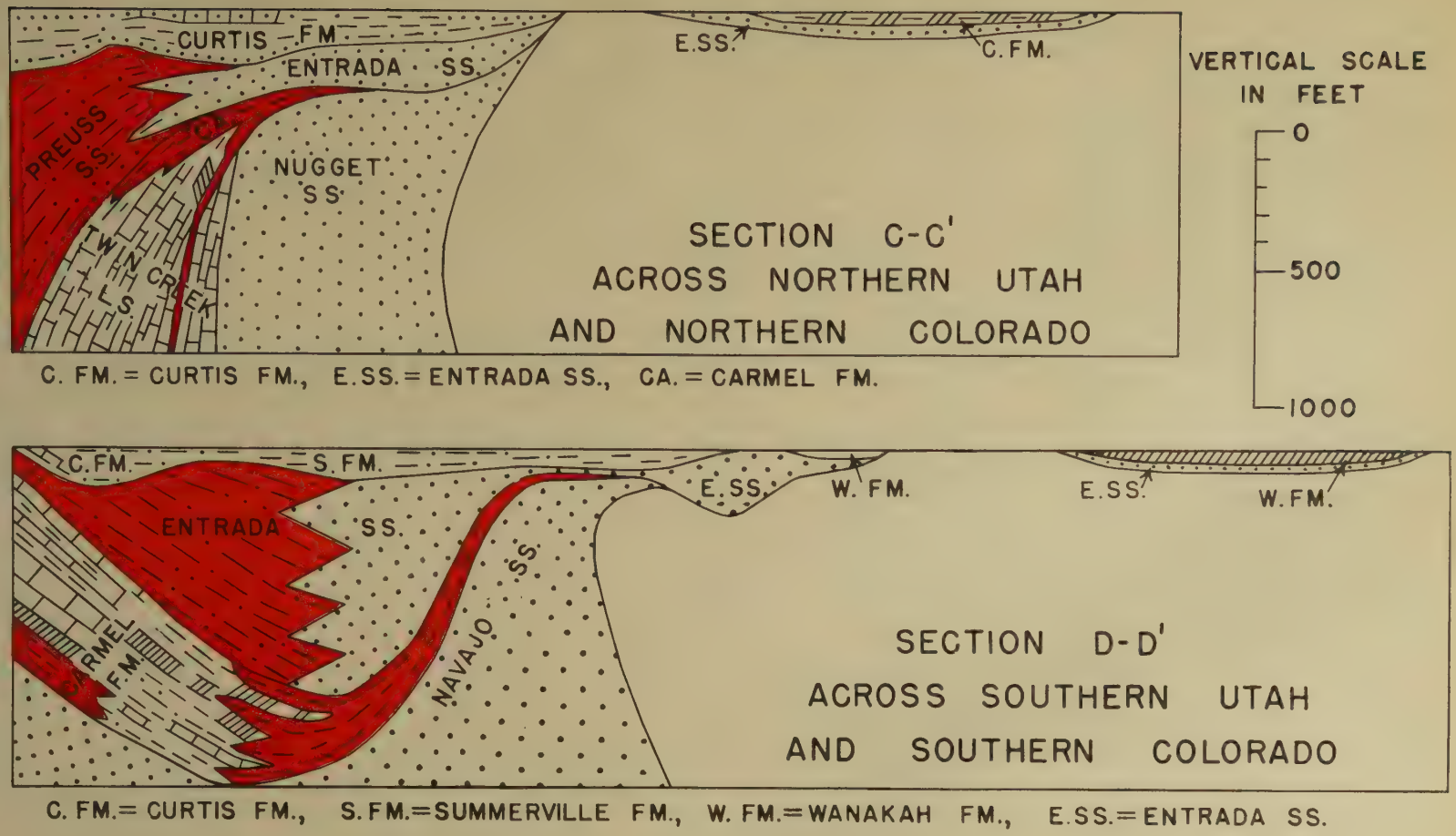


FIGURE 8 DIAGRAMMATIC CROSS SECTIONS OF JURASSIC DEPOSITS IN SOUTHERN PART OF WESTERN INTERIOR REGION

Glauconite of lower Callovian age occurs in comparable stratigraphic positions at the top of the Twin Creek limestone in Idaho, in the Hulett sandstone member of the Sundance formation in eastern Wyoming and South Dakota, and at the top of the Rierdon formation in the Sweetgrass arch of northwestern Montana. In the ripple-marked Hulett sandstone member and the upper part of the Rierdon formation the glauconite is in very small particles that contrast with the large particles of glauconite in the higher Oxfordian beds. In the ripple-marked sandy beds at the top of the Twin Creek limestone, as exposed along Preuss Creek and Thomas Fork Canyon, the glauconite is as conspicuous as in the higher Oxfordian beds (Stump sandstone) of that area. The glauconite at the top of the lower Callovian ripple-marked sandstone and sandy limestone was formed during the withdrawal of normal marine waters north of Montana, just before the deposition of unfossiliferous redbeds including the Preuss sandstone.

Glauconite is characteristic of the Oxfordian sandstone and shale throughout the western interior. It is particularly abundant in the basal sandstone, where it may be associated with water-worn belemnites and pebbles. The amount of glauconite decreases as the number of pebbles increases. On the north side of the Big Snowy Mountains the basal glauconitic sandstone is overlain directly by shale containing many large, flat oysters and belemnites. Most of the sandstone beds above the base of the Oxfordian contain a scattering of glauconite, but occasional beds are highly glauconitic. A shallow-water origin for most of these sandstones is indicated by abundant ripple marks and cross-bedding and locally by wood impressions, oölites, and such organisms as Ostrea and Gryphaea. It seems evident that the basal glauconite sandstone was deposited in very shallow water.

The greater abundance of glauconite in the Oxfordian than in the older Jurassic beds of the western interior region may be related to the western source of its sediment. Thus most of the sandstones of Middle Jurassic and Callovian age were derived from the east or southeast and were probably reworked from older sandstones. In contrast, in the Sawtooth Range of western Montana the base of the Middle Jurassic is marked by a highly glauconitic sandstone. Also, a very glauconitic ripple-marked sandstone occurs at the top of the Twin Creek limestone in southeastern Idaho. These sandstones were derived from the west or from nearby areas. The Oxfordian sandstones of western derivation contain considerable light-colored mica, suggesting that the source beds were metamorphic or igneous rocks. These possibly contained minerals more easily changed to glauconite than the particles derived from sandstones east of the Jurassic seaway. Reducing conditions, which may be necessary for the formation of glauconite (Takahashi, 1939), were more widespread in the Oxfordian than in the older Jurassic, but there are large areas in Montana and Wyoming where the lower Callovian appears to contain nearly as much organic material as the Oxfordian and still has much less glauconite. Depth of water does not appear to have been important, as some of the most glauconitic beds are pebbly or have waterworn belemnites or are associated with oyster beds. The faunas afford no basis for assuming that the temperature of the water was much different in Oxfordian time than in the older Jurassic. Probably the greater abundance of glauconite in the Oxfordian reflects the combination of several favorable factors, including especially an abundance of organic material and of minerals easily glauconitized.

Phosphate

Lenses of black phosphate nodules are fairly common in the lower and middle parts of the Sawtooth formation in the Sweetgrass arch and the Sawtooth Range in northwestern Montana (Cobban, 1945, pp. 1272-1274, 1292-1295). The nodules may be as much as an inch in diameter and commonly occur in a shaly limonitic matrix. They may be associated with oysters or other pelecypods and water-worn belemnites. The sandstone and shale in which they occur is characterized by a high bituminous content and much finely divided pyrite. They range as high as the basal shaly part of the upper siltstone member of the Sawtooth formation and are of middle Bajocian to lower Bathonian age. The maximum thickness of the beds containing the phosphate nodules is about 120 feet. This thickness, considering the time represented, shows rather slow deposition. The phosphate nodules appear to have been deposited in very shallow, stagnant waters that were receiving little sediment.

Another occurrence of phosphate is about 5 miles south-southwest of Cokeville in southwestern Wyoming. The phosphate occurs in a grayish-black oölitic limestone (Gale and Richards, 1910, pp. 508, 509) at the base of the lowest limestone member of the Twin Creek limestone.

Oölites

Oölites are widespread in the western interior Jurassic and are characteristic of certain formations and certain levels. They were formed near the beginning of the Middle Jurassic transgression as represented by the basal 10 to 20 feet of the lower limestone member of the Twin Creek limestone in southeastern Idaho and western Wyoming. They were formed widely in eastern Montana and north-central Wyoming during the middle part of the Middle Jurassic in association with limestone, dolomitic limestone, and some red shale as represented by the middle member of the Piper formation (Imlay et al., 1948). They were formed locally at the end of the Middle Jurassic in northern Montana (Cobban, 1945, p. 1275). They were formed at the beginning of the lower Callovian transgression from Idaho eastward as represented by the oölitic Canyon Springs sandstone member of the Sundance formation in South Dakota and eastern Wyoming (Imlay, 1947, p. 248), by oölitic limestone at the base of the Rierdon formation in southern Montana (Imlay et al., 1948), by thin oölitic limestone at the base of the Sundance in north-central and northwestern Wyoming, and by 200 to 300 feet of cliff-forming, partly oölitic limestone below the middle of the Twin Creek limestone in Idaho and southwestern Wyoming. They were formed locally in a retreating sea at the end of the lower Callovian as represented by the western margin of the Hulett sandstone member of the Sundance formation in north-central Wyoming and south-central Montana. They were formed widely along the eastern and southeastern margins of the Oxfordian sea as represented by the upper sandy part of the Redwater shale member of the Sundance formation of the Black Hills area in South Dakota and eastern Wyoming and by the upper part of the Curtis formation in northeastern Utah and north-central Colorado (Baker, Dane, and Reeside, 1936, p. 8; Thomas and Kruger, 1946, pp. 1279, 1287-1292). In these areas they are associated with beds of

sandstone, sandy limestone, or coquinoid limestone in a sequence that is dominantly gray shale and silty shale. They are uncommon in the Oxfordian sandstone of western Montana, southeastern Idaho, westernmost Wyoming, and central and southwestern Utah.

These occurrences and associations suggests that the Jurassic oölites were formed in the shallow, marginal parts of the seas and especially characterize the beginning and ending of marine transgressions. They are not common in the dominantly sandy or gypsiferous facies. They are apt to be associated with limestone or highly calcareous shale. Any sandstone associated with them is highly calcareous, generally passes laterally into limestone, and is less oölitic than the limestone. It appears, therefore, that two essential conditions for the precipitation of these Jurassic oölites include a large quantity of calcium carbonate and very shallow water.

Volcanic material

Bentonitic and tuffaceous beds occur in a few places in the marine Jurassic formations of the western interior and are mostly of Middle Jurassic age. Volcanic beds are not definitely known in the Callovian, although some of the soft shales in the Rierdon formation of Montana are possibly bentonitic. The marine Oxfordian likewise is nearly free of volcanic material, although one thin bed of bentonite near the top of the Curtis formation on the San Rafael Swell in central Utah was observed. This condition contrasts with that in the Morrison formation, which contains many beds of bentonite and is characterized by a greenish clayey mineral that has probably of volcanic origin.

FOSSIL ASSEMBLAGES

Middle Jurassic

Pelecypods constitute the dominant faunal element in the Middle Jurassic beds. Gastropods and cephalopods are much less abundant but include a variety of forms. Ophiuroid and holothuroid remains are abundant in washed samples of silty and sandy shales. Corals have been found at a few places. Algal-like markings have been noted in association with the coral beds. Foraminifera and Ostracoda are not numerous but they present great variety. Some of the most common species have been described (Stanton, 1899; Warren, 1932, 1947; Buckman, 1929; McLearn, 1924, 1927, 1928; Crickmay, 1936; Wells, 1942; Imlay, 1948).

The dark shales and limestones of Bajocian and lower Bathonian age in western Wyoming, southeastern Idaho, and western and northern Montana contain over 32 pelecypod genera, including pectens, limas, myas, oysters, and gryphaeas. In the thin-bedded limestones these may be associated with gastropods. The lower part of the dark shale and limestone contains ammonites, and the upper part has furnished fragmentary macrocephalitids. A few belemnites occur throughout. This assemblage apparently lived on a moderately firm calcareous mud bottom in the upper part of the neritic zone. Such forms as Ostrea and Gryphaea probably did not live much below the highest part of the neritic zone.

The faunule associated with the light-gray limestones and dolomites interbedded with red shale and gypsum in central Wyoming (Love et al., 1945) contains a few echinoids, many pelecypods, and some gastropods, with rare ammonites. It differs from the faunule in the dark limestone and shale facies principally by the presence of Opis and Nerinea and the scarcity or absence of pectens, limas, myas, oysters, and gryphaeas. It locally forms beds of coquina in a sequence that is generally poorly fossiliferous. Such a faunule appears to characterize hard calcareous bottoms bordering the seaward margin of lagoons in which gypsum and redbeds were forming.

Colonial corals occur in thin-bedded limestone several feet below the upper redbed member of the Piper formation at several places in the Pryor Mountains of south-central Montana. Some associated beds contain markings suggestive of algae, and other associated beds contain large forms of Camptonectes and macrocephalitid ammonites. The same species of corals occur in thin-bedded limestone of Middle Jurassic age near Cody, Wyo., and in southeastern Idaho. In Montana and Wyoming they are closely associated with the faunule just discussed, although not in the same beds. It seems probable that they lived on the outer margins of lagoonal barriers.

The silty to sandy beds at the top of the Middle Jurassic in northwestern Montana and in Alberta contain many pelecypods associated with ammonites and belemnites. Echinotis and Corbula distinguish this faunule from that in the dark shales and limestone and may indicate somewhat shallower waters. At least Echinotis is commonly associated with the surfaces of thin-bedded sandy limestone or sandstone.

Lower Callovian

The character of the faunal assemblage of the marine lower Callovian shows considerable variation, probably owing to the deposition of two thin mantles of sandstone along the eastern margin of the seaway and to a thick mass of limestone along the western margin of the seaway. The basal oölitic sandstone facies (Canyon Springs sandstone member of the Sundance formation) in eastern Wyoming and western South Dakota is generally poorly fossiliferous, but careful search generally reveals small oysters and fragments of Camptonectes. At a few places a fairly large faunule has been obtained, consisting of the ammonite Arcticoceras, the gastropod Lyosoma, 15 genera of pelecypods, and the brachiopod Lingula. Tracks and burrows are common. Probably most of the Canyon Springs sandstone member was deposited in the littoral zone, but locally some beds were deposited in the upper part of the neritic zone.

The ripple-marked Hulett sandstone member of the Sundance formation, marking the top of the Callovian throughout eastern Wyoming, southeastern Montana, and the Dakotas, is impoverished faunally, although columnals of Pentacrinus and fragments of Camptonectes may be found in nearly every section. The pelecypod Quenstedtia was found at one locality and is the only other fossil noted. Deposition in the littoral zone is suggested by the abundance of ripple marks and the fragmentary condition of the fossils.

The silty to sandy Stockade Beaver shale member lying between the Canyon Springs sandstone member and the Hulett sandstone member of the Sundance formation is characterized by an abundance of the pelecypod Echinotis adhering to hard, thin layers of limestone or sandstone or concretions of limestone. It is especially abundant near the base of the member, which is generally less sandy than the upper part. Common associated pelecypods include oysters, pectens, and myas. Gryphaea nebrascensis Meek and Hayden is rare near the southeastern margin of the shale facies, as in the Black Hills and the Hartville uplift, but becomes common northwestward as the shale becomes less sandy. Lingulas are fairly common in dark shale and concretionary limestone and become less common westward. Uncommon fossils include Pentacrinus columnals, belemnites, and brittle stars or starfish. The ammonite Arcticoceras occurs near the base of the shales. Microfossils include an abundance of Foraminifera, Ostracoda, parts of echinoids, holothuroids, ophiuroids, and scolecodonts. Ostracodes greatly dominate in the more sandy part of the Stockade Beaver shale member but become less common than the Foraminifera westward (personal communication by A. R. Loeblich). Deposition in the shallowest part of the neritic zone is indicated by the occurrence of Lingula and Ostrea. Deepening of the sea westward is indicated by an increase in the number of gryphaeas and a decrease in the number of lingulas and by a similar relationship between the abundance of Foraminifera and Ostracoda.

A lower Callovian shale facies with interbeds of limestone occurs throughout central and western Montana (Rierdon formation) and northwestern Wyoming. Mollusks are common in shales associated with limestone. Microfossils are abundant throughout and present the same forms as in the Stockade Beaver shale member of the Sundance formation. A few Bryozoa have been found either attached to Gryphaea shells or free. Brachiopods are represented at a few places by terebratulids, rhynchonellids, and lingulas. The pelecypods are associated mainly with the limestone beds and include 28 genera. The most common pelecypods are Pleuromya and Gryphaea. Echinotis and Quenstedtia are uncommon. Naticoid gastropods are common in the basal beds associated with the large Pecten-like Ctenostreon, various myas, and ammonites. Belemnites occur throughout but are uncommon. Ammonites are abundant locally and represent four distinct zones. Arcticoceras occurs in the basal few feet of the Rierdon formation associated with Cadoceras, Procerites, and Gryphaea impressimarginata McLearn. It is succeeded directly by Gowericeras associated with Cadoceras, rare specimens of Grossouvria and Arcticoceras, and abundant Gryphaea nebrascensis. The middle part of the formation has furnished Kepplerites and Cadoceras. The highest beds equivalent to the Hulett sandstone member of the Sundance formation contain many ammonites. The assemblage in the Rierdon formation differs from that in the Stockade Beaver shale member of the Sundance formation by a greater abundance of ammonites, myas, gryphaeas, limas, and astartes and a rarity of such forms as Echinotis, Quenstedtia, Tancredia, and Lingula. This difference probably reflects a westward deepening of the sea, but the presence of such forms as Ostrea, Gryphaea, Mytilus, Echinotis, and Lingula certainly indicates nothing deeper than the top of the neritic zone.

A limestone facies of lower Callovian age is represented by the upper two thirds of the Twin Creek limestone of southeastern Idaho, westernmost Wyoming, and north-central Utah. This facies is marked basally by 200 to 300 feet of thin- to medium-bedded, partly oölitic cliff-forming limestone. This is overlain by 400 to 1,500 feet of shaly to thin-bedded limestone. Above follows about 200 feet of silty to sandy, ripple-marked, thin-bedded limestone that passes westward into a sandstone. These units are singularly unfossiliferous. The basal limestone contains an occasional Gryphaea. In the shaly limestone a few hard beds bear Camptonectes, Pinna, Pentacrinus, and belemnites. Rarely a bed contains such forms as Ostrea, Lopha, Gryphaea, Isocyprina, or Astarte. The upper silty to sandy limestone contains an abundance of Pentacrinus columnals and fragmentary Camptonectes. All these units become thinner and shalier eastward in west-central Wyoming and pass into a highly fossiliferous interbedded shale and limestone facies typical of the Rierdon formation. The general scarcity of fossils in the Twin Creek limestone cannot be ascribed to deposition in deep water because of the presence in some beds of Ostrea and Gryphaea. The scarcity is probably due to unfavorable bottom conditions induced by rapid subsidence and equally rapid sedimentation in a sea saturated with calcium carbonate.

Oxfordian

Belemnites are the most characteristic fossils in the Oxfordian beds of the western interior. They are abundant in the shales and fairly common in the sandstones. Pelecypods are fairly abundant in thin interbeds of limestones and sandstones of the shale facies that is dominant in the eastern part of the Jurassic seaway and are rather uncommon in the sandstone facies farther west. In the shale facies they include 22 genera and probably were deposited in the shallow part of the neritic zone. In the sandstone facies, as in western Montana, western Wyoming, and southeastern Idaho, the pelecypods are abundantly represented by a dozen genera. Most of those are shallow-water forms, but the presence of Mytilus suggests deposition of the sandstone partly in the littoral zone as does the presence of ripple marks and cross-bedding, numerous wormlike burrows, and trails. Ammonites occur most commonly in concretions in the shale facies, although in central Montana they occur locally as external molds and as pyritized internal molds. Occasionally an external cast is found in a sandstone bed. At the base of the Oxfordian sequence in the Little Rocky Mountains and the Bearpaw Mountains in central Montana the characteristic ammonites are Quenstedtoceras (Bourkelamberticeras) and Q. (Pavloviceras). With these are associated a few specimens of Prososphinctes, Cardioceras (Maltoniceras), and C. (Scarburgiceras). Directly above these beds is another assemblage of ammonites characterized by many specimens of Scarburgiceras, a subgenus of Cardioceras. This ammonite assemblage is widespread in the western interior region near the top of the lower third or the lower half of the Oxfordian. Associated ammonites include Goliathiceras, Pachycardioceras, various subgenera of Cardioceras, and Grossouvria (Poculisphinctes). A few cardioceratids have been found in the middle part of the Oxfordian beds. Rhynchonellid brachiopods are locally abundant in sandy and oölitic limestone and in thin-bedded calcareous sandstone. Crinoid columnals and echinoid spines and plates are common in the sandstones and limestones. A

few brittle stars have been found on sandstone surfaces in eastern Wyoming and western South Dakota. Washed samples contain numerous fragments of ophiuroids, holothuroids, echinoids, and crinoids. Foraminifera occur in the shaly beds in great numbers and variety in contrast to the Ostracoda. Corals of reef type occur in the basal pebbly sandstone of the Stump sandstone in southeastern Idaho and of the Swift formation in the Centennial Mountains in southwestern Montana. The corals appear to be worn and are associated with cidarid spines, crinoid columnals, and oysters. They were probably derived by erosion of coral beds in the Twin Creek limestone, as the same species occur near the base of that formation in southeastern Idaho. It seems unlikely that reef corals would range from middle Bajocian to Oxfordian, since even the species of pelecypods have changed completely in that interval.

ECOLOGIC IMPLICATIONS OF SUCCESSIVE FOSSIL ASSEMBLAGES

Mollusks and foraminifers were much more abundant in species and individuals than other kinds of life in the Jurassic sea of the western region. Among the mollusks, the pelecypods far outnumbered the gastropods in species and individuals. They were somewhat more common than cephalopods during the Middle Jurassic and the Callovian but were probably outnumbered by them during the Oxfordian, when the sea swarmed with belemnites. Gastropods were relatively common locally during the Middle Jurassic and lower Callovian and were practically absent in the Oxfordian. The pelecypods are most abundant in thin-bedded calcareous sandstone or thin-bedded limestone, the gastropods are most common in thin-bedded limestone or in concretions in shale, and the belemnites are somewhat more common in shale than in sandstone or limestone. Ostracodes outnumbered the foraminifers numerically only during the lower Callovian in a sandy to silty clay facies deposited along the eastern part of the seaway but at all times presented less variety than the foraminifers. Ophiuroids, holothuroids, crinoids, and echinoids were fairly common, as washed samples of sandy to silty shale contain their skeletal elements in abundance. Apparently the echinoids were much less common during the Oxfordian than earlier in the Jurassic. Rhynchonelid and terebratulid brachiopods are unknown in the Middle Jurassic, are common locally in chalky to sandy limestones in the lower Callovian, and are fairly common in sandy beds in the Oxfordian. Associated fossils, as well as the character of the enclosing sediments, indicate that they lived in the shallowest part of the neritic zone. Lingulas are fairly common in shales and siltstone deposited in the eastern part of the lower Callovian sea but become less common westward as the sediments become more calcareous and gryphaeas become more abundant. The presence of lingulas suggests extremely shallow waters. Corals occur rarely in the Middle Jurassic limestone. The presence of worms is indicated by some Serpula-like tubes in limestones and by many burrows on the surfaces of sandstone. Trails are common in the Oxfordian sandstones. Plesiosaur remains have been noted in the lower Callovian shales of western Montana and in Oxfordian shales in South Dakota. Fish remains have been found in lower Callovian shale in South Dakota and in Oxfordian limestone in Colorado and New Mexico. Evidence of plant life consists of some algal-like markings in Middle Jurassic limestone and of many pieces of driftwood in the Oxfordian sandstones of western Montana.

Of these fossils, only the mollusks are sufficiently well known to establish the presence of successive zones reflecting organic and environmental changes. The gastropods of the Middle Jurassic occur in coquinoid or slightly sandy, thin-bedded limestones overlying redbeds and include such forms as Nerinea, Nododelphinula, Procerithium, Neritina, and Lyosoma. The last three genera occur also at the base of the Callovian in nodular, sandy, or oölitic limestone, generally in association with a large naticoid gastropod, a large Pecten-like pelecypod, Ctenostreon, and many myas. Evidently these organisms lived on a hard calcareous substratum in very shallow water at the beginning of the Callovian transgression. Nerinea has not been recorded above the Middle Jurassic in the western interior, although common throughout the Mediterranean seas during Jurassic and Lower Cretaceous time. Its absence during the Upper Jurassic in the western interior may be related to the absence of corals in the same area and may possibly signify a cooler climate than during the Middle Jurassic. The general absence of gastropods above the base of the Callovian may be ascribed partly to scarcity of a firm substratum on which to live. However, there are many beds in both the Callovian and Oxfordian that appear to be suitable in this respect. Other factors, such as depth of water or temperature, must be involved. Temperature is probably important, as the Jurassic deposits of Alaska and Greenland contain few gastropods. This may be explained by the nearly complete absence of limestone in the Jurassic of those areas. However, the absence of limestone may itself be related to temperature.

Many of the pelecypod species range through the Middle Jurassic into the lower Callovian, but some new species appear in the Callovian. Few species range from the Callovian into the Oxfordian. This faunal change reflects a break in sedimentation during the middle and upper Callovian, when marine waters withdrew from the western interior of the United States an unknown distance into Canada. Some benthonic pelecypods, such as Astarte, Trigonia, Pleuromya, Grammatodon, and Pinna, were adapted to a considerable range of environment, as they lived on sandy, shaly, and limy bottoms. The free-swimming Camptonectes lived under similar conditions although most abundantly on limy and sandy bottoms. Mytilus has been found mainly in the Canyon Spring sandstone member of the Sundance formation and in the Oxfordian sandstones of western Wyoming, western Montana, and southeastern Idaho, which are considered to be partly littoral deposits. It is commonly associated with Ostrea but not with Gryphaea and probably represents shallower water and sandier bottoms than those in which Gryphaea thrived. On less sandy limy bottoms lived such forms as Cucullaea, Nucula, Ctenostreon, Oxytoma, Plagiostoma, Gryphaea, Ostrea, Lopha, Gervillia, Volsella, Pholadomya, Panope, Homomya, Goniomya, Cercomya, Pleuromya, Protocardia, Lima, and Inoceramus, which are characteristic of thin beds of nodular or oölitic or slightly sandy limestone that are interbedded with shaly limestone and shale. On softer mud bottoms, represented now by shaly limestone and shale, lived such forms as Isocyprina, Thracia, Pleuromya, Pholadomya, Panope, Astarte, Trigonia, and Pinna. The pelecypod assemblage occurring in the Middle Jurassic dolomites and limestones associated with gypsum and redbeds differs from that in ordinary dark-gray limestone and shales by the presence of Opis and Corbis and the scarcity or absence of pectens, limas, myas, oysters, and gryphaeas. Associated fossils generally include many gastropods, of which Nerinea is most common.

Among the cephalopods, the nautiloids have been found only in the middle Bajocian limestones of Utah and Idaho and the lower Callovian limestones of Montana, the belemnites range throughout the marine Jurassic but are uncommon below the Oxfordian, and the ammonites are fairly common locally at most levels except the lower Bathonian and the upper Oxfordian. The ammonites are represented by a number of short-ranged genera that permit accurate correlation with the Jurassic of the Arctic region and of northwest Europe, as discussed elsewhere (Imlay, 1948). Stephanoceratids dominated in the Bajocian, macrocephalitids in the Bathonian, cardioceratids and kosmoceratids in the Callovian, and cardioceratids in the Oxfordian. Perisphinctids occurred sparingly in the upper Bathonian, Callovian, and lower Oxfordian. The ammonites of the Middle Jurassic and the Callovian occur most abundantly in thin-bedded limestones that are interbedded with calcareous shale and contain a variety of benthonic pelecypods. They appear to have favored slightly silty or sandy limy bottoms. Their frequent occurrence in silty or sandy limestones suggests that they lived in about the same place where they were buried. They are extremely rare in thick-bedded or ripple-marked sandstones. The ammonites of the Oxfordian occur either in highly calcareous thin-bedded sandstones and sandy limestones in a shale sequence or in limestone concretions in shale or as pyritic molds in shale. In the sandstones and in some of the larger concretions they are commonly associated with such pelecypods as Ostrea, Grammatodon, Pleuromya, Proeconia, Protocardia, Echinotis, Tancredia, Astarte, Camptonectes, Pinna, and Volsella and the belemnite Pachyteuthis. Vertebrae of a plesiosaur were found with them in one concretion. The occurrence in sandstone and sandy limestone presumably represents a natural association that was buried suddenly. The occurrence of many benthonic pelecypods in some of the larger concretions suggests that the pelecypods were living on a locally hard spot on the sea floor. Such local colonies would explain the abundance of fossils in a few concretions and the lack of fossils in most concretions. On the other hand, some very small limestone concretions contain many small ammonites and are not likely a place where the ammonites lived but are possibly a place where they were trapped. The presence of pyritized ammonites in the lower part of the Oxfordian shale in the Little Rocky Mountains of north-central Montana is unusual in the Jurassic of North America, although common in the Jurassic of Europe. Their presence suggests locally stagnant waters. Such a condition was favored by a position about midway in the Jurassic sea and considerably removed from sources of sediment. From these associations it is evident that the ammonites avoided the shallow waters in which gypsiferous redbeds and dolomitic limestones were forming or in which sands were being extensively agitated by waves and currents but were generally common elsewhere. The absence of ammonites in the dense, shaly limestone forming most of the upper part of the Twin Creek limestone in southeastern Idaho and westernmost Wyoming is probably related to the scarcity of pelecypods on which they fed and may be explained either by bottom conditions unfavorable for benthonic life or to greater-than-normal salinity of the sea water.

One of the most interesting ecological problems is why belemnites are much more abundant in the Oxfordian of the western interior than in the underlying Jurassic. The most likely explanations involve differences in depth or temperature of the sea or in the food supply. Of these factors, the food

supply seems most important, as there is no faunal or lithologic evidence that the Oxfordian sea was appreciably deeper or different in temperature from the Callovian sea. A greater quantity of organic matter in the Oxfordian sea than in the earlier Jurassic seas is indicated by the much greater abundance of glauconite, suggesting reducing conditions, by the generally dark color of the shales, and by the presence of many pieces of driftwood in the Oxfordian sandstone along the western part of the seaway in Montana. These plant remains show that the landmass to the west was covered with vegetation and was capable of furnishing organic sediments and minerals, such as phosphate, to the seas.

At any rate, the much greater abundance of belemnites in glauconitic sandstones than in some other kinds of sediments has been noted in the Upper Cretaceous of the Atlantic and Gulf coasts of the United States (personal communication of L. W. Stephenson; Dorsey, 1917). In contrast, belemnites are exceedingly rare in the Upper Cretaceous of the western interior, which has very little glauconite (personal communication of J. B. Reeside, Jr.). It should be noted, however, that belemnites are locally abundant in Europe in Upper Cretaceous chalks and in Lower Jurassic dark shales, as well as in some greensands. All three types of sediment reflect an abundance of organic material at the time of deposition and hence suggest that the abundance of of belemnites is related to their food supply.

COMPARISONS WITH EXISTING SEAS

Comparison of the Jurassic sea of the western interior with existing seas is difficult because of its extended lobate shape, its position in the center of a continent, its vast expanse and shallowness, its connection only with the Arctic region, the presence of broad swells and low islands that hindered marine circulation, and the general low relief of the bordering lands until near the end of the period. Hudson Bay, the North Sea, the Baltic Sea, and the Barents Sea cannot be compared, because their sediments are mainly of glacial origin (Gripenberg, 1939; Luders, 1939; Shepard, 1939, pp. 225-227). The Mediterranean and the Gulf of Mexico are much deeper bodies of water. The Red Sea is much smaller, and its bottom is reported to have little animal life (Strøm, 1939, p. 365). The Florida-Bahama region is bounded by major oceans, although its deposits are somewhat comparable to those formed during lower Callovian time along the western part of the Jurassic sea. The Java Sea and the southern part of the South China Sea (Myers, 1945) probably compare in shallowness with the Jurassic sea of the western interior, but the bordering lands have considerable relief and parts of these seas have only recently been submerged. However, it seems likely that future ecologic and sedimentational studies in these seas will afford interesting comparisons with former epeiric seas.

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ECOLOGY OF NONALGAL MARINE PLANTS[13/]

by

Roland W. Brown[14/]

Land plants, adapted to saline soils and environments, have spread to the edges of salty inland lakes and along seacoasts, estuaries, lagoons, and marshes, subject to tidal influences and other marine conditions. Some of these plants, such as mangroves, grasses, and sedges, have, so to speak, stepped out into the coastal waters. Submerged in the brackish and marine waters themselves, however, with the exception of algae and fungi, are relatively few "higher" plants. These include no mosses, liverworts, ferns, or gymnosperms—only about 50 or 60 species of flowering plants—all monocotyledons. Of these, several are economically important. Eelgrass (Zostera marina) is a favorite food of waterfowl, and Cymodocea manatorum is the food of the manatee or seacow. As most of these plants grow in dense patches or submarine fields, they afford shelter for many kinds of animal life.

Just when this invasion of the sea by "higher" plants took place is unknown. Perhaps some algae and fungi have always been marine, but it is hardly likely that any of the "higher" plants began life as such in salty water. No authentic fossils of these marine flowering plants, except mangroves and grasses, have been taken from marine or brackish-water deposits. Such deposits may, however, contain remains of many kinds of inland terrestrial plants. For example, late Jurassic and early Cretaceous strata in Alaska and California yield ferns, cycads, and ginkgos, mixed with marine invertebrates. The intercalation of animal-bearing marine or brackish-water strata with the coal seams of most of the great coal deposits of the late Paleozoic, Cretaceous, and early Tertiary, indicates that these plant-bearing coals and associated shales and sandstones developed at or near sea level and not far inland from a sea.

The ups and downs of coastlines; that is, changes in sea level, may be reflected in the deposits formed in littoral salt marshes. The plants entombed in these deposits are useful evidence of such records, as exemplified in citations of the accompanying bibliography.

Whatever may be the effect of plants on marine ecology, the reverse should not be overlooked. Oceans and ocean currents play a considerable part in the dispersal of plants, especially those whose seeds are adapted to floating and survival for a long time in salt water. Debris of land plants, swept by streams into the sea, may be carried by currents for a long distance, but the chances of much of it, except the toughest, such as wood, seeds, and leathery leaves, resisting for long the many agents of destruction, are poor. Such debris buried quickly in a coastal delta at the mouth

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14/ Geologist, U. S. Geological Survey.

of a stream may yield valuable clues to the composition and ecology of the flora of the adjacent land; but material carried for some distance by ocean currents before burial may be quite inharmonious with the land flora at that latitude. Therefore, any interpretations of climate and ecology, based on remains of land plants in marine strata, should be received with caution.

The following bibliography is not intended to be complete but to give clues for further pursuit of the subject by the interested reader.

BIBLIOGRAPHY

Bartlett, H. H. The submarine Chamaecyparis bog at Woods Hole, Massachusetts: Rhodora, vol. 11, pp. 221-235, 1909.

The author concludes that the floor, at the greatest depth of sounding in this Quamquisset bog, on which the white cedar (Chamaecyparis thyoides) began growing and on which peat began to be deposited, once stood 16 feet higher than at present, or, in other words, that subsidence of 16 feet has occurred. He also claims that the history of the marsh is a reversal of that of a typical marsh, as described by Shaler, in that the vertical arrangement of the strata is reversed although the order of the two (Spartina) zones from the sea landward is the same.

Brown, Roland W. Section at Stiles (North Haven Brick Co.) clay pit, opposite Montowese. In Flint, R. F., The glacial geology of Connecticut: State Geol. and Nat. History Survey Bull. 47, pp. 263-266, 1930.

This section, in the Quinnipiac Valley, 2 miles south of North Haven, Conn., is within a few miles of salt water. Varved red clay (Pleistocene) at the base of the section exposed in the clay pit is now 8 feet or more below sea level. The red clay is unconformably overlain by cross-bedded sands containing logs of white oak, black oak, maple, and hemlock, and the sands are topped by from 2 to 5 feet of silty peat composed largely of the tidal-marsh grasses Spartina alterniflora and Phragmites communis. The base of the peat is now at sea level. None of the wood found in the sands has been bored by Teredo, thus suggesting that the sands were deposited in fresh water.

_____. Fossil plants from the Colgate member of the Fox Hills sandstone and adjacent strata: U. S. Geol. Survey Prof. Paper 189, pp. 239-275, 1939.

The Fox Hills sandstone, at its type locality and over a wide area in the Rocky Mountains and Plains region, is marine and contains marine fossils. Landward, however, brackish- and eventually fresh-water facies appear. The flora described in this paper is a land flora. One item (p. 253) in the list of fossils, however, occurs in the shore facies of the formation and was originally described as a seaweed, Halymenites major Lesquereux (see Phymatoderma dienvalii Watelet in Plantes fossiles du bassin de Paris, p. 24, pl. 4, fig. 1, 1866). Halymenites was once considered to be diagnostic of the Fox Hills sandstone, but it is now known to occur in both older and younger formations and to have a widespread distribution. Its chief stratigraphic significance is that it indicates a near-shore zone. The suspicion is growing that Halymenites is not a seaweed or other plant, but the burrow of some marine animal, perhaps a crustacean.

Croneis, Carey, and Grubbs, David M. Silurian sea balls: Jour. Geology, vol. 47, pp. 598-612, 1939.

The authors here compare siliceous nodules from Niagara dolomite with modern "sea balls" and "lake balls" and attribute their origin to wave action during storm periods. The nodules may be without fossils, or they may contain a considerable invertebrate fauna. Footnotes give citations to other papers on the subject.

Davis, C. A. Salt marsh formation near Boston and its geological significance: Econ. Geology, vol. 5, pp. 623-639, 1910.

In this paper Davis claimed that the subsurface sections of salt marshes near Boston contained no eelgrass (Zostera marina), as previously postulated by Shaler for the initiation of salt marshes, but that in some instances the section was composed of fresh-water organisms and sediments, and in others, where no fresh-water deposits occurred, the peat was composed of the silty remains of the tidal-marsh grasses Spartina alterniflora and Spartina patens.

Davis, John H., Jr. The ecology and geologic role of mangroves in Florida: Carnegie Inst. Washington Pub. 517. Papers from Tortugas Laboratory, vol. 32, pp. 303-412, 1940.

In this study of land building along the southern Florida coast Davis describes at length the role of mangroves in the process. Seedlings of red mangrove (Rhizophora mangle) become established in the bottom sands, either siliceous or calcareous, of an outer zone in water that seldom covers the plants more than 6 inches. In due course the new plants develop leaves and prop roots, the latter becoming not only effective anchors for the plants but also traps to catch sediments and other debris. In the lee of the mature forest of red mangroves, with which are associated some marine algae and aquatic seed plants, are open stands of black mangrove (Avicennia nitida) interspersed with other salt-marsh associates, especially the white mangrove (Laguncularia nitida). This zone may be inundated by every average tide over its outer part, but its inner part may be free from such action. A transitional zone, seldom, if ever, flooded between the mangrove communities and the inland forest vegetation, is composed of buttonwood (Conocarpus erecta) and many other hardwoods. The large aquatic and aerial fauna found in these zones makes its contribution to the sediments accumulating as sands, marls, peats, and mucks. Thus soils are built up to ever higher levels, with consequent outward extension of the coast line. It may thus be possible to utilize mangrove plantings in building up and protecting coastal soils. Study of the deep peats may reveal evidence of sea-level and other coastal changes.

Fossil remains of Avicennia, Conocarpus, and Laguncularia have been reported by Berry from the lagoonal deposits of the Wilcox formation (Eocene) and remains of Rhizophora from the Claiborne and Jackson formations (Eocene) of the Gulf Coast of the Southern States. He has also reported Avicennia, Conocarpus, and Rhizophora from the Pleistocene of Oropouche, Trinidad.

Deevey, Edward S., Jr. On the date of the last rise of sea level in southern New England, with remarks on the Grassy Island site: Am. Jour. Sci., vol. 246, pp. 329-352, 1948.

Archaeological and other data from salt marsh, coastal pond, and inland bog deposits in southern Massachusetts indicate a postglacial rise in sea level, there being as much as 20 feet of salt marsh peat, composed essentially of the grass Spartina patens, locally overlying fresh-water swamp deposits with forest remains in place. Says the author: "Because of the complexity of the problem and the insufficiency of the evidence, therefore, all that is known about the rise of sea level in New England is (1) that it has taken place, and (2) that it was a postglacial event. We do not know (3) how extensive it was, (4) whether it was equally extensive throughout the region, or subject to systematic regional differences which might imply crustal warping. Nor do we know (5) when it began, or (6) when it ended, there being no agreement on whether the rise is still going on or has stopped within the last few years or centuries". Inasmuch as archaeological materials on Grassy Island in the Taunton River, near Taunton, Mass., lie on a surface of till and sand now 40 inches below present mean low tide, the author is inclined to accept as reasonable a date of about 600 years ago for the rise in sea level at that locality.

Essig, E. O. The Ruppia balls of Little Borax Lake: Sci. Monthly, vol. 66, pp. 467-471, 1948.

When this little lake in California dried up, vegetable balls composed of Ruppia maritima, a pondweed common in brackish and marine waters along coasts and in saline waters of the interior, were found in great numbers near high watermark on the east shore. Excellent photographs of these balls illustrate the paper.

Fontaine, William M. Notes on some fossil plants from the Trinity division of the Comanche series of Texas: U. S. Nat. Mus. Proc., vol. 16, pp. 261-282, 1893.

Lower Cretaceous marine limestones known as the Glen Rose limestone immediately overlying the basal sand of the Trinity group, 2 miles above Glen Rose on the Paluxy River, Tex., contain ferns, cycads, and conifers, but no known angiosperms. All the materials are fragmentary, and all are of the predominantly tougher kinds or parts of plants that can best withstand fluviatile and marine transportation for some distance. Consequently, these fossil materials probably represent only a small fraction of the actual land flora of early Cretaceous time in that region of Texas.

Kindle, E. M. Concerning "lake balls", "Cladophora balls", and "coal balls": Am. Midland Naturalist, vol. 15, pp. 752-760, 1934.

The "balls" here discussed are the rounded, compact masses of vegetation sometimes formed in fresh-water lakes. However, the author refers to several papers that describe "sea balls". The bibliography covers the subject to that date.

Knight, J. Brookes. A salt-marsh study: Am. Jour. Sci., vol. 28, pp. 161-181, 1934.

The marsh here discussed is on the shore of Long Island Sound, at Killams Point, east of New Haven, Conn., and is, according to the author, a good example of the Shaler hypothesis of salt-marsh formation along the coast of the Northeastern States. Sections of the marsh reveal molluscan shell beds interbedded with peaty layers composed of the grass Spartina alterniflora. Topping these is the fibrous peat of Spartina patens without mollusks, but as its base is 3 feet below present high-tide level, there has evidently been a rise of sea level since that peat began forming.

MacKay, A. H. Water-rolled weed balls: Nova Scotian Inst. Sci., Proc. and Trans., vol. 11, pp. 667-670, 1906.

These balls are from lakes in Nova Scotia, but the specimens figured are "sea balls" found on the seashore at Upper Kingsburg.

Moldenke, Harold N. Marine flowering plants: Torreya, vol. 40, pp. 120-124, 1940.

In this paper the author discusses the 10 genera and about 50 species of known marine flowering plants, giving pertinent details about their environmental conditions. All the species are monocotyledons.

Ridley, Henry N. The dispersal of plants throughout the world. 1930.

This is a detailed discussion of the methods of dispersal of living plants.

Shaler, N. S. Sea-coast swamps of the eastern United States: U. S. Geol. Survey Ann. Rept. 6, pp. 359-398, 1885.

This is a general discussion of the reclamation of coastal areas by the growth of salt-marsh grasses and other herbaceous vegetation along portions of the coast of the Northeastern States. The process is said to begin in the silted-up shallow portions of estuaries or barrier-protected lagoons, where eelgrass (Zostera marina) gets a foothold and traps sediments and organic debris. The salt-marsh grasses Spartina alterniflora and Spartina patens in turn, together with muds and animal remains, complete the development of the marsh unless interrupted. The grassy vegetation of these marshes is in striking contrast with the mangrove and associated woody growths of the coastal marshes of the Southeastern States.

_____. General account of the fresh-water morasses of the United States, with a description of the Dismal Swamp district of Virginia and North Carolina: U. S. Geol. Survey Ann. Rept. 10, pt. 1, pp. 255-339, 1890.

Although the author is here primarily concerned with an explanation of fresh-water swamps, particularly the Dismal Swamp, he devotes several pages to a discussion of the marine or brackish marshes along the coast of the Southeastern States. He records his observations of mangroves and their role in initiating a catchment basin for sediments and organic debris, resulting eventually in a peaty or marly marsh.

White, David. Value of floral evidence in marine strata as indicative of nearness of shores: Geol. Soc. Am. Bull., vol. 22, pp. 221-227, 1911.

After quoting Agassiz and others concerning the dredging of vegetable debris from considerable depths and at some distance from shore, White remarks: "At best the leaf fragments reported appear to have been confined to types with hard, siliceous, or thick cuticles, such as the palm and the bamboo. Only thick, leathery, dicotyledonous types like the orange and the mangrove seem to have been in recognizable condition in the dredging near the land. Only in very rare cases do we find any quantity of land plant material under the conditions of deposition of the purer carbonates at any considerable distance from the coast, and in these cases the material embraces only the more imperishable parts of the plants.

"The significance of the evidence offered by plant remains found fossil in marine deposits depends mainly on the state of their preservation. If the material is macerated, corroded, rolled, defoliated, skeletonized, incrusted, or bears other signs of having been for some time in the water, it is liable to have been transported for some distance, judgment of the possible distance or time being dependent to an extent on the progress of the work of the destructive agencies. If long in sea water the fragments are likely to bear the marks of the abundant marine organisms, particularly if in tropical sea water ... In most marine sediments the only vestiges of land plants that may be found are confined to the most indestructible parts—that is, seed envelopes, spore covers, pollen shells, and fragments of wood and stems, especially of resinous or very dense types".

PALECECOLOGY OF THE AGNATHA

by

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There have been few attempts to discuss the paleoecology of the Ostracoderms. As Clements pointed out regarding paleoecology in general (Geol. Soc. America Bull., vol. 29): "the ecological contributions of paleontology have usually been a by-product of taxonomic, phylogenetic, or stratigraphic studies, and their ecological orientation has been difficult or uncertain". Practically all the literature on the paleoecology of the Agnatha consists of brief paragraphs scattered through the literature, or more commonly of isolated statements interpolated in stratigraphic or taxonomic descriptions. Most of these statements deal only with speculations as to the general habitat of the group. Others concern feeding habits, locomotion, etc., but seldom is there any attempt to determine the associations of which they formed a part.

One of the major difficulties in the way of analyzing the ecology of this group is that the fossil associations are, as Wasmund has put it, not biocoenoses but "thanatocoenoses"; i.e., death associations. Thus the ostracoderms from the Upper Silurian of Oesel are found in a dolomitic limestone along with invertebrates, some of which; e.g., cephalopods, were marine. Two interpretations of this assemblage have been given. The ostracoderms and eurypterids have been held to be fresh water forms whose remains drifted down stream and became lodged in the sediments with those of marine forms. They have also been held to be parts of the marine assemblage.

The present bibliography is not exhaustive, and it is hoped that additional items may be discovered.

Abel, O.
Lehrbuch der Paläozoologie. Jena 1920.

This work includes a discussion, on pp. 14-15, of the relation between mode of life of prehistoric animals and habitat to place of burial. The Anaspida are held (p. 320) to have been found only in fresh-water deposits. All Osteostrachi are benthonic marine forms; only Pteraspids had a more active mode of life.

Ami, H. M.
Knoydart formation of Nova Scotia: Geol. Soc. America Bull., vol. 12, 300-312, 1901.

This is mostly stratigraphic. The suggestion is made (p. 312) that the ostracoderm-containing deposits were shallow water lacustrine sediments. Ami suggests the name "Lake Pictou" for these deposits, and "Lake Chaleur" for the similar beds in the Campbelltown area of the Bay of Chaleurs.

Berry, E. W.
The environment of the early vertebrates: Am. Naturalist, vol. 59, pp. 354-362, 1925.

This paper is directed chiefly against Chamberlin's argument that vertebrates must have originated in streams. Berry states that the earliest ostracoderm remains are in marine deposits and that their habitat was marine.

Bridge, T.
Fishes (exclusive of the Teleostei): Cambridge Natural History, vol. 7, 1904.

On page 531 occurs the statement that the ostracoderms were grovelling, bottom-feeding, sluggish forms.

Brotzen, F.
1. Erster Nachweis von Unterdevon im Ostseegebiete durch Konglomeratgeschiebe mit Fischresten. Part I.: Zeitschr. für Geschiebeforschung, vol. 9, pp. 55-63, 1933.

The stratigraphy and fauna are discussed. On page 60 the facies containing the agnatha is described as a typical transgression-conglomerate with a marine fish-fauna.

2. Erster Nachweis von Unterdevon im Ostseebebiete durch Konglomeratgeschiebe mit Fischresten. II. Paläontologischer Teil: Zeitschr. für Geschiebeforschung, vol. 10, pp. 1-65, 1934.

Pages 54-61 include a discussion of the habitat. Brotzen argues for a marine habitat. Concentration of fossils accompanied by similarity of faunas seems to indicate a common habitat and not stream contributions. The invertebrate assemblage is marine. He further suggests marine littoral zone.

3. Beiträge zur Vertebratenfauna des Westpodolischen Silurs und Devons. I. Protaspis arnelli n. sp. und Brachipteraspis n.gen. latissima Zych: Arkiv. för Zoologi K. Svenska Vetenskapsakademien, vol. 28A, pp. 1-52, 1936.

Pages 42-44 include a discussion of the occurrence and ecology of Protaspis and Brachipteraspis. Marine habitat indicated with deposition in a strand environment. Some ostracoderms were fair swimmers, others benthonic. Probably all mud-grovellers.

Bryant, W. L.
1. The fish fauna of Beartooth Butte, Wyoming. Part I. The Heterostraci and Osteostraci: Am. Philos. Soc. Proc., vol. 72, pp. 285-314, 1933.

Deposits regarded as stream-bed. (p. 286).

2. Cryptaspis and other Lower Devonian fossil fishes from Beartooth Butte, Wyoming: Am. Philos. Soc. Proc., vol. 75, pp. 111-141, 1935.

The deposits regarded as in fresh or brackish water under estuarine conditions in a drowned river valley.

3. A study of the oldest known vertebrates, Astraspis and Eriptychius: Am. Philos. Soc. Proc., vol. 76, pp. 409-427, 1936.

Shallow water habitat is indicated.

Dorf, E.
Stratigraphy and paleontology of a new Devonian formation at Beartooth Butte, Wyoming: Jour. Geology, vol. 42, 1934.

Beartooth Butte deposits are regarded as occurring in quiet water in a drowned river valley or an estuary.

Eastman, C. R.
Devonian fishes of Iowa: Iowa Geol. Survey, vol. 18, 1908.

Ostracoderms were mud-grovelling inhabitants of the shallow seabottom (p. 54).

Gross, W.
Die Wirbeltiere des rheinishen Devons. Teil II: Preuss. Geol. Landesanst. Abh. N. F., vol. 176, pp. 5-83, 1937.

The habitat is discussed (p. 78) and the statement is made that the marine character of the fauna is undoubted, the habitat being shallow coastal waters.

Heintz, A.
The Downtonian and Devonian vertebrates of Spitsbergen. II. Suborder Cyathaspida. Part I. Tribe Poraspidei, Family Poraspidae: Skrift. om Svalbard og Ishavet, vol. 40, 1935.

Poraspis was benthonic in habitat (p. 125).

Kiaer, J.
The Downtonian fauna of Norway. I. Anaspida, with a geological introduction: Kristiania, Videnskaps. Selsk. Skrifter. Math.-Nat. K., no. 6, 1924.

The deposits are flood-plain, the habitat fresh water.

Lindström, G.
On remains of a Cyathaspis from the Silurian strata of Gotland: Bihang till K. Svenska Vetenskapsakademien Handlingar, vol. 21, pp. 3-15, 1895.

The association is described (p. 11) and regarded as that of calm water in a sheltered bay where mud was being deposited.

Meek, A.
The migrations of fishes. London 1916.

The deposits in which ostracoderms occur are mainly those of fresh water. He suggests possible andromous migration from the sea.

Obruchev, D.
1. Yoglinia n.g., Latest pteraspid from the Middle Devonian of the Leningrad district: Acad. des Sci. USSR, C. R. (Dokl.), vol. 41, pp. 41-43, 1943.

The habitat was transitional from marine (lagoonal) to fluviatile.

2. An attempted restoration of Psammosteus paradoxa: Acad. Sci. USSR, C. R. (Dokl.), vol. 42, pp. 143-145, 1944.

The habitat was calm lagoon waters, the habit bottom-living, ooze-feeding.

3. The Evolution of Aganatha: Acad. Sci. USSR Proc., vol. 24, pp. 257-272, 1945. (In Russian).

While dealing chiefly with phylogeny this does restore Pteraspis and Psammolepis as mud-grovellers.

Raymond, P.
The Anaspida and the problem of the origin of the vertebrates: Am. Jour. Sci., 5th ser., vol. 10, 1925.

The Anaspida were nectonic, all other ostracoderms benthonic.

Robertson, G. M.
1. The ostracoderm genus Dartmuthia Patten: Am. Jour. of Sci., 5th ser., vol. 29, pp. 323-335, 1935.

The habitat is given as probably fresh water.

2. The Trematapidae: Am. Jour. of Sci., 5th ser., vol. 35, pp. 172-206; 273-296, 1938.

Habit and habitus are discussed (pp. 185-186). The trematapids are associated with marine invertebrates in sediments which are either marine or lagoonal. The habitat may have been either fresh water or marine. The cephalaspids were benthonic, sluggish, feeding on small invertebrates or scavenging in the mud. Trematapids were probably more active, but essentially similar in habit.

3. Some aspects of evolutionary theory: The Aerend, vol. 13, pp. 113-128; 145-167. Reprinted in Fort Hays Kans. State College Studies. Sci. Ser., no. 1, 1942.

The ostracoderms were varied in their habitat and in adaptation to food sources. (p. 127).

Romer, A. S.

1. Eurypterid influence on vertebrate history: Science. n.s., vol. 78, pp. 114-117, 1933.

Ostracoderm habitat was fresh water, or at most brackish. Probably were prey for eurypterids.

2. The early evolution of fishes: Quart. Rev. Biol., vol. 21, pp. 33-69, 1946.

Ostracoderms were bottom-living, their habitat fresh water or estuarine. The significance of their armor was as protection against the predaceous eurypterids. (pp. 43-46).

3. (and Gove, B. H.). Environment of the early vertebrates: Am. Midland Naturalist, vol. 16, pp. 805-856, 1935.

This is chiefly devoted to analysis of whether or not fresh water was the earliest habitat of the vertebrates. In a detailed analysis of the various occurrences of ostracoderms the conclusion is reached that they were probably fresh water inhabitants, the occurrences in association with marine invertebrates being explained as due to streams transporting their remains into the sea.

Säve-Söderbergh, G.

Remarks on "Downtonian" and related vertebrate faunas: Geol. Föreningens i Stockholm Förhandlingar, vol. 63, pp. 229-244, 1941.

This paper is chiefly stratigraphic. He refers to "continental beds" as being the source of the ostracoderm remains discussed.

Stetson, H. C.

A New American Thelodys: Am. Jour. Sci., 5th ser., vol. 16, pp. 221-231, 1928.

This anaspid was a mud-groveller.

Westoll, T. S.

A new cephalaspid fish from the Downtonian of Scotland, with notes on the structure and classification of ostracoderms: Royal Soc. Edinburgh Trans., vol. 61, pp. 341-357, 1945.

Pteraspids were primarily bottom-dwellers, but capable of excursions into higher layers.

White, E. I.

1. The ostracoderm Pteraspis Kner and the relationships of the agnathous vertebrates: Royal Soc. London Phil. Trans. B., vol. 225, 1935.

A British occurrence of ostracoderms seems to represent the contents of a single dried-up pool, which makes the association more significant.

2. New pteraspids from South Wales: Quart. Jour. Geol. Soc. London, vol. 94, pp. 85-115.

The habitat is given as marine "or at any rate access to the open sea".

3. The genus Phialaspis and the 'Psammosteus Limestones': Quart. Jour. Geol. Soc. London, vol. 101, pp. 207-242.

The assortment indicates flood-water action; i.e., a washing in of animals, probably fresh water. (pp. 214-216).

Woodward, A. S.

1. The oldest fossil fishes: Nature, vol. 115, pp. 124-125, 1925.

The occurrences are in shallow water deposits. He quotes Kiaer's opinion that the anaspids of Norway occur in deposits of fresh water lakes on a flood plain.

2. Modern progress in vertebrate paleontology: Huxley Memorial Lectures. 1931.

The habit and habitat of ostracoderms was varied, from freely swimming to mud-grovelling.

TYPES OF OCCURRENCE AND POSITION OF BRYOZOA IN LATE PALEOZOIC SEDIMENTS OF THE MIDCONTINENT

by

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Position of Bryozoa in cyclic sedimentation. Since J. Marvin Weller (1930) re-discovered what is now known as cyclic sedimentation and the resulting "cyclothems" in the Pennsylvanian of Illinois, the phenomenon originally demonstrated by Udden (1912, fig. 2, p. 27), much has been written in America on sedimentary cycles, megacycles, etc. in the Pennsylvanian and lower Permian of the Midcontinent and Appalachian region. In nearly all instances the lithologic approach was used, and biologic aspects of cyclic sedimentation were only vaguely considered, if not entirely ignored. Greater use of fossils in cyclic sedimentation was made by some European scientists (Hudson, 1924; Tcherryshew, 1931), and a study of repeated regular succession of biologic facies, indicative of advance and retreat of the sea, was attempted by Elias (1937) for the lower Permian (Big Blue) sediments of Kansas. It was demonstrated that in the beds of the Big Blue series Bryozoa occur together with calcareous brachiopods in the medium-deep phases of the local marine invasions, that is in the "brachiopod" and "mixed" (brachiopod-molluscan) phases of the Permian marine cycles. The subsequent extension of the study of the cyclic sedimentation into the Pennsylvanian and Mississippian of this country fully sustains the conclusion previously reached from studies of lower Permian sediments; namely, that Bryozoa are generally associated with the articulate or calcareous brachiopoda, and that they are not known to be associated with Lingula in the Lingula phases, or with mollusks in the pure molluscan phases of the marine cycles, that is they are absent in the shallowest water phases. On the other hand, they are also rarely present in the fusulinid phase, which belongs in the deepest part of the local sedimentary cycles.

Judging from the distribution of marine Bryozoa in the modern seas, there seems to be no reason why they should not be found both in the shallowest and the deepest waters of the late Paleozoic inland seas. At present they range from shallowest to deepest waters in the Mediterranean and other inland seas, and also in the oceanic bays the world over. Nevertheless, all observations indicate that, at least in as far as the known calcareous cryptostomatous and trepostomatous Bryozoa are concerned, they occur, unless found quite alone, almost exclusively with the calcareous brachiopods. On the other hand it is quite possible that some chitinous Paleozoic Bryozoa could have existed at all or nearly all depths where marine Bryozoa occur in modern seas, but their remains have not been found. However, the microscopic adnate and shell-penetrating ctenostomatous Bryozoa (the study of which has been developing comparatively slowly: Ulrich and Bassler, 1904; Condra and Elias, 1944), which at least in part were chitinous, have been found so far only in the same phases of the cycle where the other preserved Bryozoa occur.

While it would be too sweeping to state that no Bryozoa of any kind lived in either the shallowest or the deepest waters of the known Paleozoic seas, there exist sufficient grounds to suggest that the Bryozoa in these waters were probably rare. Their apparent absence in the shallowest near-shore deposits may be explained by the following reasoning.

The local deposits nearest the shore consist of three common types: (1) gray and buff sands, sandy shales, sandstones and conglomerates, containing some coals; (2) red and green silts to sands and sandstones; and (3) black muds, usually compacted to black fissile shale. The sediments of the first type seem to represent mostly deltaic accumulations, which are generally unsuitable for Bryozoa that need, as a rule, clear water and a more or less hard and stable substratum for attachment of their colonies.

In the silty sediments of the second type, which are of generally finer texture than those of the first type, there are usually no fossil remains of any kind preserved, but remains of mollusks, often in form of molds only, are occasionally observed, usually in green silts and sandy shales; the reason for the absence of Bryozoa in these sediments is in part the same as in the case of the sediments of first type, and in addition it seems probable that their remains could be a subject of quick disintegration and dissolution, much like the known shells of clams and gastropods whose molds occur in them. The shells of these swimmers and crawlers apparently were quickly dissolved after coming to rest upon the bottom subsequent to their death.

The bottoms covered with toxic black muds, which were subsequently compacted into black shale, apparently presented very special conditions of life unsuitable for most animals and plants. On the other hand, these conditions suited Lingula and some other inarticulate brachiopods, and were perhaps most instrumental in the survival of these primitive shells from the Paleozoic to the present. In the black fissile shales of the Midcontinent only a few selected clams and less frequently a very few calcareous brachiopods are found, but Bryozoa have not been encountered. It seems that even though the shells of both calcareous and chitinous brachiopods did not suffer rapid dissolution or disintegration in these black muds, the conditions remained prohibitive for the Bryozoa because the water over such bottom was seldom, if ever, clear. The clay particles of black mud were so fine that even the gentlest stirring of water above them, caused by movements of various bottom dwellers (crawling, burrowing, up and down moves within the open holes, expulsion of water or gases, etc.), probably kept the water clouded all or nearly all of the time.

The reason for the absence or near absence of Bryozoa in the deepwater fusulinid phase is seemingly the same as the reason for the absence or near absence in it of all other marine organisms, such as brachiopods, mollusks, corals, etc. Two kinds of occurrence of fusulines may be recognized. In the more common instance they are extremely gregarious, so that a bed of rock, or a zone within it, may be properly called fusulinid rock or phase. Ordinarily no other identifiable organic remains of any kind are observable in them, except, in some instances a few specimens of Ottonosia or Osagia, which are compound crustose lumps made of adnate Foraminifera and simple

algae. But even these adnate forms have almost never been found to encrust dead shells of fusulines, but invariably encrust fragments of other shells that seem to get mixed in this fusulinid association accidentally. Hence it seems that the gregarious fusulines appropriates some parts of the sea bottom so exclusively, as to make it practically prohibitive for life of any other organisms.

On the other hand, some species of fusulines, at least under special circumstances, were more widely scattered upon the bottom of the sea and in such occurrences they shared the bottom with both Bryozoa and brachiopods.

Types of occurrences of the Bryozoa. As stated above, the common occurrences of the Bryozoa are in the brachiopod and mixed phases of the local late Paleozoic marine cycles. When complete or nearly complete zoaria are encountered they are distributed in the following four types of occurrence. (1) They are scattered several times their own diameter apart, and brachiopods, horn corals, some fusulines, and other invertebrates are associated with them, being also widely scattered. Such occurrence of the scattered biota is reminiscent of the distribution of the invertebrates in the bottom of modern seas, and apparently illustrates a similar distribution when alive upon the silty bottoms of the late Paleozoic seas. The fact that in such associations many individual shells are found in their natural orientation, such as the ventral valve in a shell of a spiny brachiopod facing downward, coral in erect position with initial part pointing downward, etc., makes this conclusion reasonably certain. (2) In the second type of occurrence the Bryozoa are encountered growing close together and forming small "nests", usually made of less than ten individual zoaria, some of which may be connected to each other. A few comparatively small brachiopods are occasionally associated with them in such "nests". (3) In some instances a great number of Bryozoa are concentrated to form a layer, which is so crowded with their zoaria that it is usually called by field geologists a bryozoan layer or bed, such as Fenestella bed, Archimedes bed, etc. In this fashion the fenestrate Bryozoa are encountered in the Dinantian of the British Isles and western Europe, and in the upper Mississippian and Pennsylvanian of America; Archimedes and the accompanying Fenestella in the Upper Mississippian of America; and in other occurrences.

By comparison with the distribution of the bryozoa in modern seas the second and third types are reminiscent of the gregarious occurrence of living bryozoa in the "seccas" of the Bay of Naples, as described by Johannes Walther (1910). A "secca" is a local name for a marine bank or small reef encountered at depths from 135 to 240 feet, elevated some 60 feet and at some points up to 120 feet above the surrounding bottom, and occupying areas up to a mile across. Gregarious Bryozoa make turfs which occupy patches up to 200 yards long upon the higher parts of seccas, usually grading laterally into patches of gregarious calcareous algae, the Bryozoa frequently attached to them. Together with the Bryozoa these algae make up the principal biota of the banks. Twenty five species identified by Walther as belonging to both principal living orders of Bryozoa, Cheilostomata and Cyclostomata, are abundant. Small brachiopods are associated with them, while the larger Terebratula lives abundantly in the surrounding muds. All Bryozoa were encountered growing upon broken shells and crustose calcareous algae but none were encountered living in the mud.

The turf-like gatherings of living Bryozoa in seccas perhaps simulates most closely their mass-occurrence in the late Paleozoic; but in seccas they do not intertangle so as to form anything like vertical growth above the turf level, a situation encountered only in some late Paleozoic strata, as in the following type. (4) Most peculiar and economically important are the occurrences of masses of Bryozoa in which the fenestrate growth forms are entangled so as to produce vertically elevated reeflike structures. In this fashion bryozoan biostromes, a few inches to a few feet thick, occur in the Permian of western Texas. In the upper Uralian (Upper Pennsylvanian) and Lower Permian of the Urals the same type of bryozoan associations build the so-called "shihany," or huge reefs, which serve as reservoirs of petroleum in the newly producing areas west and southwest of the main Ural Ridge. Petroleum-producing reefs in western Texas and the adjacent part of New Mexico seem to be also built principally by the fenestrate bryozoan entanglements of the same type.

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